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FIGURE OF MERIT STUDIES OF BEAM POWER CONCEPTS FOR ADVANCED SPACE EXPLORATION

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ABSTRACT

Surface - to surface, millimeter - wavelength beam power systems for power transmission on the lunar base have been investigated. Qualitative/quantitative analyses and technology assessment of 35 GHz, 110 GHz and 140 GHz beam power systems have been conducted. System characteristics including mass, stowage volume, cost and efficiency as a function of range and power level were calculated. A simple figure of merit analysis indicates that the 35 GHz system would be the preferred choice for lunar base applications, followed closely by the 110 GHz system. System parameters of a 35 GHz beam power system appropriate for power transmission on a recent lunar base concept studied by NASA Johnson Space Center and the necessary deployment sequence are suggested.

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1. INTRODUCTION :

Power for space exploration missions can be supplied by either solar, nuclear (direct power systems coupled to the spacecraft or the user) or by beaming at microwave, millimeter and optical frequencies (lasers). Power beaming is a relatively new concept and needs to be effectively compared with the direct power systems for the different missions under consideration, in order to determine where beaming would be a feasible concept. We were commissioned by the Mission Assessment and Applications branch and the Power Technology division of NASA Lewis Research Center to investigate the applicability of beam power for NASA's advanced space exploration missions and develop a figure of merit model (FOM) for comparison purposes. The original objectives of our programme were :

- Develop a figure of merit model to assess applicability of beam power technology to NASA's exploratory missions.
- Apply the figure of merit model to Code Z's FY '88 exploratory case studies and any other relevant cases, in order to compare beam power with other alternatives.
- Examine whether beam power technology enhances the case studies analyzed or consider modifications and extensions of the missions toward that goal.
- Conduct a technology assessment of beamed power systems where it is a recommended scheme (if it is necessary) in order to make beam power an acceptable technology for advanced space missions.

Figure 1 shows the methodology for the figure of merit model which is discussed below. The model is forced by mission data relevant to determining a choice of a power system which is input. At the time it was assumed that the missions that would be considered by us would be the NASA Code Z's exploratory case studies from the Office of Exploration's FY'88 technical report [1]. It was also hoped that as the study progressed sufficient flexibility would be built into the process so that the FOM model could be coupled directly with either the Large Scale Programs Institute - Lunar Base Model (LSPI - LBM) or the SAIC - Mars Mission Performance Generator (SAIC - MMPG). New / other exploratory mission data from case studies such as "Asteroid Exploration and Utilization " or "Lunar Oasis " [2] being conceptualized by the Mission Analysis and Systems Engineering? (MASE) at Johnson Space Center (JSC) and other potential missions would also be eventually evaluated with regard to powering them, utilizing the FOM process.

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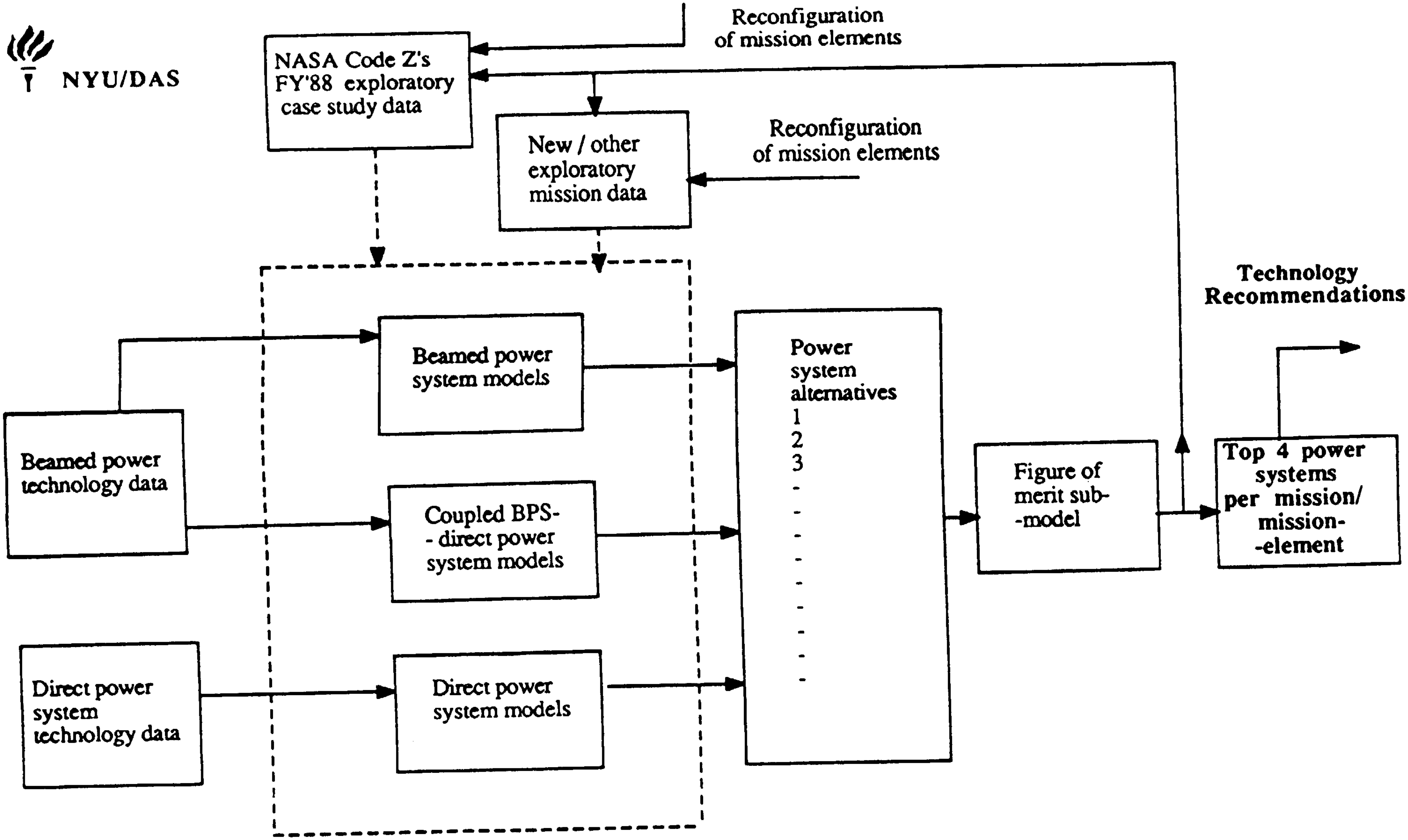


OVERVIEW OF FIGURE OF MERIT MODEL

In order to compare beam power systems (BPS) and direct power systems (DPS) a technology assessment would be necessary, in order that relevant data can be supplied to an FOM model. Possible applications require investigating the state - of - the art of beam power technology over a large range (frequencies) of the electromagnetic spectrum. Component data for laser systems, would include that of the laser, transmit optics and reception and conversion devices. In the case of the microwave system data, would be necessary for components such as RF generators, antennas, rectennas, power conditioning and thermal management at different frequencies. Direct power systems are defined as power systems that can be integrated with the mission / elements directly. Examples of such systems include nuclear; such as the SP -100, Radioisotope Thermionic Generator's (RTG's), different Photovoltaic technologies, dynamic converters; like the Sterling Engine and fuel cells, etc for which data collection would have to be initiated.

In addition to data, system models would have to be formulated for beam and direct power systems, with the technology data serving as input. These models would calculate system characteristics like mass, size, volume, cost, etc and operating parameters. Besides system characteristics, power reception models to calculate power link parameters such as, antenna sizes, beam efficiency, etc for both the microwave power transmission schemes (example, surface beaming to different points of utilization) and laser power transmission alternatives need to be set up. Numerous references on space power have developed direct power system models which calculate system characteristics and could be integrated into a study of this kind or developed especially for this.

Once the models for the power systems are developed, trade off studies can be performed with the aid of these models, for each mission separately. A special figure of merit sub - model would then be constructed which would select the best means of powering a given mission/mission element. Several algorithms have been developed for this procedure elsewhere and the simplest of these is explained and used in section 4. Beam power in itself is a simple concept, however it can be deployed in several configurations, in every mission, some of which are :

- Surface power generation coupled with point-to-point power beaming.
- Power generation onboard a spacecraft (like the SP-100 or an equivalent solar power satellite - SPS) and power beaming to the surface.
- Power generation onboard a spacecraft and power beaming to the surface, with subsequent beaming to points of utilization.
- Surface power generation and beaming to the point of utilization using an orbiting reflector.

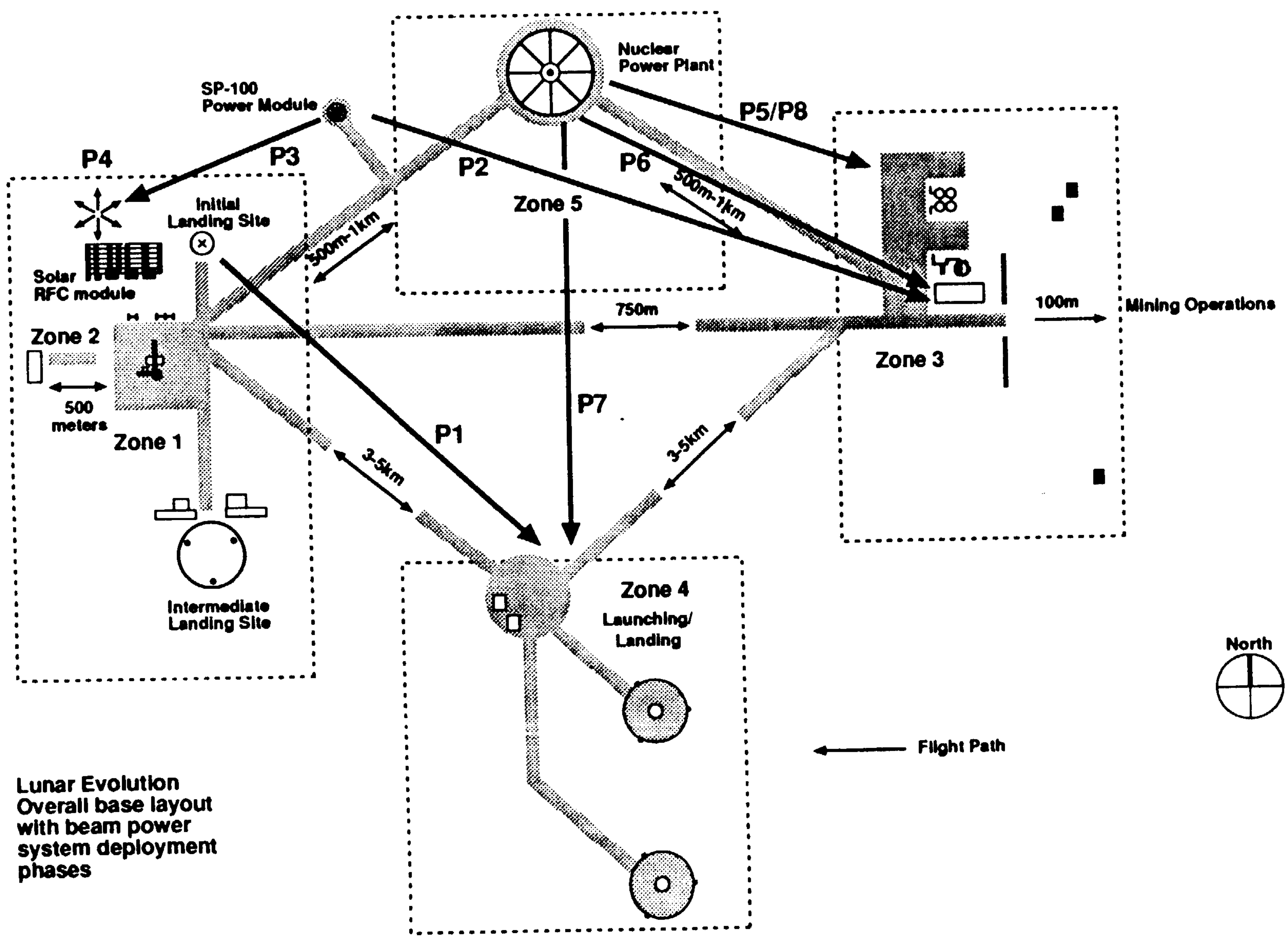
Very few trade off studies have been done to date on beam power and even of these studies, only the first two configurations on the list have been studied, at either millimeter (mm) or optical frequencies. Christian, [3] has conducted a trade off study on the use of power beaming to support mobile power loads such as rovers, construction and mining equipment and explorers . Power beaming to the Lunar base at mm frequencies from orbiting power satellites has been investigated by Cull [4], while Faymon has done a qualitative [5] assessment of microwave beam power. Trade off studies at optical frequencies are more profuse in number, and most of them use almost the same assumptions and analysis techniques. However, from a limited survey of the literature on lasers, we feel that except for the systems analysis of megawatt iodide lasers [6] most studies are a first cut, and unless additional refinements are added and methods of analysis clarified, these studies cannot be incorporated into a FOM study. Laser technology is in a very preliminary state of development as compared to the microwave systems, which no doubt only adds to the difficulty of making quantitative statements about the technology.

The lack of prior study severely hampered our efforts in developing a grandiose FOM model of the kind we proposed earlier. Further one can appreciate the enormity of the task, when it is realized that not only laser, microwave and direct power systems would have had to have been modeled and compared, but that the procedure should be made flexible enough that the same FOM model could be run for numerous missions. Fortunately for us at this stage, with President Bush's announcement for a commitment to a lunar and Mars base, we were specifically asked by the sponsors to redirect our efforts and focus on the surface - to - surface beaming of power on the lunar base effort being studied at JSC.

The alternatives available for surface - to - surface power transmission on the lunar base are cables and power beaming. This study was restricted to high frequency RF, i.e., millimeter waves. This study considered three frequencies, namely 35 GHz, 110 GHz and 140 GHz beam power systems (BPS). A power reception efficiency analysis model formulated by Hoffert et al[7,8] for the case of microwave power transmission from earth based transmitters to orbiting satellite constellations, has been extended in this study . The model in the present format can be used to analyze the power transmission for either orbiting satellites beaming power to the surface of a planetary body / moon or for point - to - point power beaming in addition to the case mentioned above. The model in the present study has been intercompared with other power reception models that were developed earlier and they show good agreement.

The beam power system essentially consists of a power source, power conditioning system, an RF generator, an antenna and a rectyfying antenna (rectenna). A technology assessment has been conducted in order to evaluate the state - of - the art of the components of the BPS. A systems analysis has been conducted in order to determine the major parameters of the BPS at the three

System Architecture



Lunar Evolution
Overall base layout
with beam power
system deployment
phases

frequencies. Mass, stowage volume, cost and system efficiency are the major system characteristics calculated for a range of power levels from ~ 10 KW to 800 KW, for ranges (the distance between transmitter and rectenna) up to 6 Km. In arriving at these estimates numerous parameters of the component subsystems had to be determined. A simple figures of merit analysis has also been been conducted in order to intercompare these three BPS's and one of them is shown to be more suitable for the JSC lunar base concept.

2. THE LUNAR BASE :

Commemorating the 20th anniversary of the first moon landing, President Bush, in a speech at the National Air and Space Museum, declared "And next, for the new century, back to the moon, back to the future, and this time back to stay," thus establishing a firm U.S commitment for a lunar base [9]. Many questions have been raised about the rationale for a lunar base and about the ability of the nation to bear the fiscal responsibility of a large space endeavor of this kind. Using projections of the nation's GNP and assuming a fixed percentage of the federal outlays for the space program, Sellers and Keaton [10] concluded that the lunar base was a fiscally attainable goal.

Except for the extended periods of time spent on the Soviet Mir space station, man has not yet learnt to live and work in the environs of space, and the moon would be the most logical place to begin. The moon would in a sense become a stepping stone to the planets of the solar system and beyond. The resources of the moon like oxygen, silicon, iron, titanium, etc could be used to further space exploration and also provide economic returns for the space program. A recent study points out that it would be economically more viable to build solar power satellites in GEO using lunar resources than in stages from earth launched materials [11]. The far side of the moon, shielded from earth's electronic noise would be an ideal place for astronomy. Noise from various sources is a major problem for either orbiting or earth based observatories. Orbiting missions like the Solar Max satellite have had gamma rays from Soviet RORSAT's (Radar Ocean Reconnaissance Satellites) interfering with astronomy [12]. A lunar observatory will offer an enhanced resolution and unique viewing ability over terrestrial and orbiting telescopes. The rationale, benefits and spin - offs of the lunar base are many fold and are discussed elsewhere.

An excellent account of the evolution of the lunar base concept dating back from 1638 to post Apollo has been given in references [13] and [14]. Many locations including that of a polar site, far side observatory and return to the Apollo sites whose topography and environment are well known have been proposed. Irrespective of location or concept, powering the base will be a major issue and is the focus of attention of this study. A recent lunar base concept [15] studied at JSC was used in this study to analyze some of the issues related with power generation and transmission, though the analysis and results of this study are not restricted to any specific concept.

The layout and the zones of the JSC concept are shown in figure 2. Zone 1 is the habitat and the science users are located in zone 2. A solar photovoltaic panel coupled to a regenerative fuel cell (RFC) is shown close to zones 1 and 2. An SP - 100 nuclear power system is isolated and placed about a kilometer from the habitat. Zone 3 is the ISRU (In - situ resource utilization) region where the mining is conducted and the LOX (lunar oxygen) plants are situated and zone 4 is the launch, landing and support zone. Zone 5 is the region where the megawatt nuclear power plant is situated. Figure 3 shows an artist's concept of such a lunar base, with power being beamed from an SP - 100 nuclear reactor in the background. To the west of the reactor is the habitat and the solar - RFC system. To the east is the ISRU zone and the LOX plant to which power is also being beamed. Antennas are attached to a tower near the SP - 100 at different heights, in order to achieve beaming to multiple ranges. In the foreground a construction vehicle appears to be moving away toward the launch, landing and support zone.

Power is essential in order to conduct the scientific experiments, the mining and oxygen extraction operations, to provide support for the launch and landing pad, for the habitat and for routine operations such as communications, thermal control, construction and maintenance and life support. Once power is generated it must be delivered to the users. Power transmission is achieved by means of power beaming at millimeter - wave frequencies. The steps involved in the transmission of power are 1) power is generated by either a solar PV system or by nuclear reactors, 2) the voltage is stepped up by use of either a transformer (in the case of an AC input) or an inverter (in the case of DC input) 3)the power is converted to RF by use of appropriate conversion devices 4) the power is then fed to an antenna, which beams the power across to where the user is located 5) the power is intercepted by a rectifying antenna, which also converts it to DC 6) this power appropriately conditioned is fed to the user.

The lunar night lasts for approximately fourteen earth days, which necessitates either power storage or nuclear reactors. In order to shield personnel from the radiation hazards due to these reactors, it is required that they be isolated. Power beaming provides a flexible way to provide such an isolation. The arrows with the acronyms P1 (Phase one) through P7 (Phase seven) in figure 2 represent paths of power transmission flows in this scenario. The term phase here is used in the context of the deployment sequence necessary over the years as the power loads and capacity grow. Figure 4 shows the increase of the stationary power requirements for the lunar base concept. The term stationary power implies that additional power will be necessary for mobile systems like rovers, construction and mining equipment, long range explorers, etc. There is a difference in the day and night capacities due to solar insolation or the lack of it.

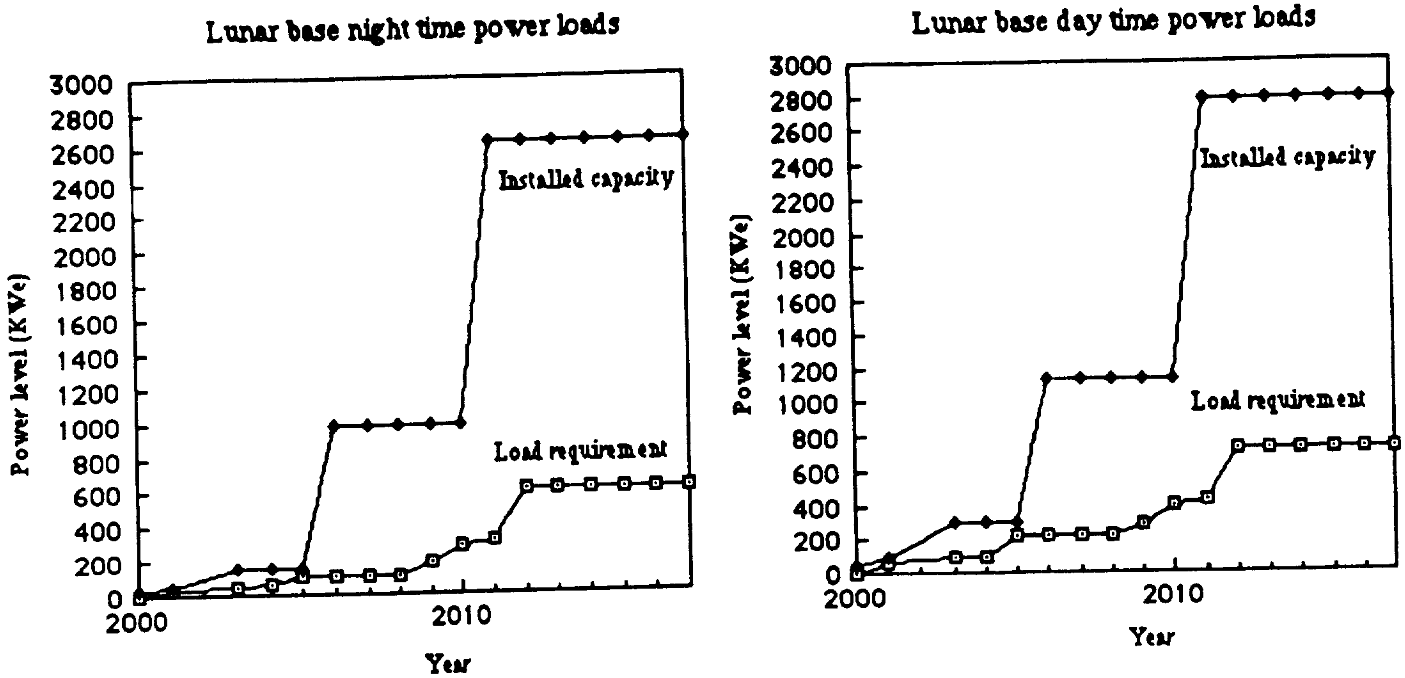


Figure 4 : Depicts the growth in the stationary power loads and the installed capacity in the lunar base concept analysed at the NASA Johnson Space Center. Variation in day and night power is primarily caused by solar insolation.

3. ASSESSMENT OF BEAM POWER TECHNOLOGIES :

The major components of the beam power system are a power conditioning system, an RF generator an antenna and a rectyfying antenna (rectenna). Numerous RF generation devices are available at millimeter frequencies including reflex klystrons, traveling wave tubes, extended interaction oscillators / amplifiers, Gunn oscillators and gyrotrons. The constraint that determines choice of one technology over the other is the power level that needs to be transmitted. Most solid state devices are available off the shelf, at low power levels thus driving the choice to power tubes. The only power tubes that can generate RF power at the kilowatt level on a CW (continuous basis) as against a pulsed mode are gyrotrons. Gyrotron availability at high power levels in turn confines choice of frequency to three or four points in the millimeter band. This is because most of the other components i.e, the antenna, the power conditioning, the rectenna are either available or to a degree are frequency independent. Antenna systems at millimeter frequencies are either available or under development, power conditioning is under development for the Space Station Freedom program and the SDI program and rectenna development at 35 GHz is under progress and higher frequency rectennas are being designed. If the beam power system is the chosen for power transmission either on the lunar or Mars bases, an integrated beam power system for deployment must be available well within the next decade. This dictates that the choice of frequency be made well in advance and design, development, test and evaluation (DDT&E) efforts be focussed on improving performance of component sub - systems at these frequencies. We have thus restricted our investigation of beam power systems to 35, 110 and 140 GHz, since high power CW gyrotrons have been developed at these frequencies.

From the limited survey we undertook, to gather data on gyrotrons, we found that they are commercially available at 35, 110, 140 and 240 GHz. Much of the gyrotron work has been done by either Varian or Thomson - CSF, though the Naval Research Labs (NRL) and other agencies

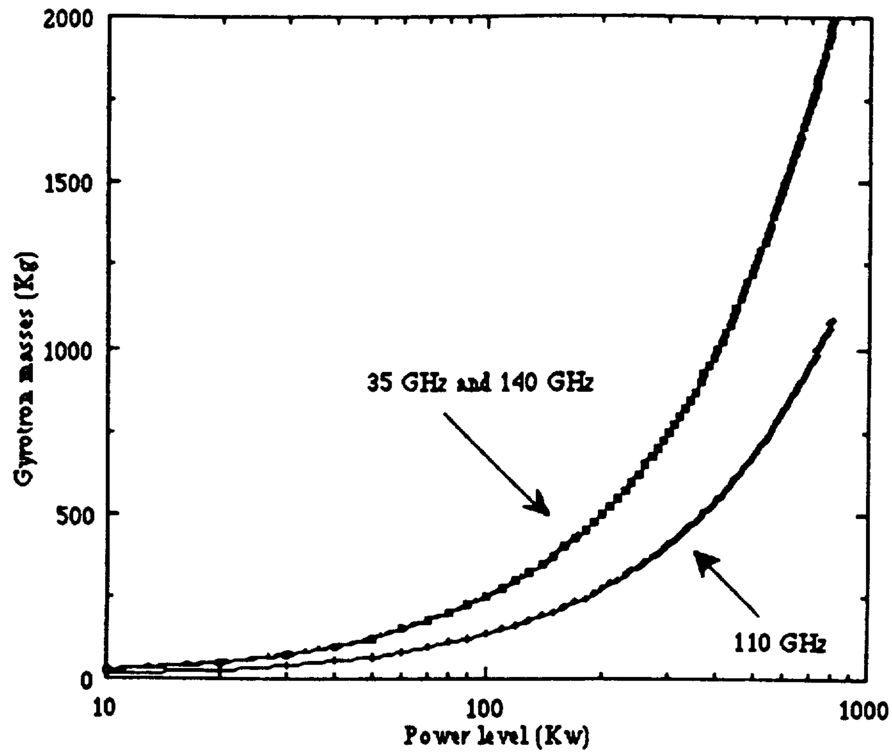


Figure 5 : Shows the scaling of gyrotron masses with power level. This scaling was performed using data provided by Varian.

have been working in this area as well. We have based our data for gyrotrons primarily on that provided to us by Varian. The gyrotron is a microwave oscillator in which an electron beam interacts with a DC magnetic field due to the cyclotron resonance condition, which is :

$$\omega_c = n\ \omega$$

where n is an integer, ω is the frequency and ω_c is the cyclotron frequency given by :

$$\omega_c = \frac{e\ B}{\gamma m_o}$$

Here, e is the charge on an electron, m_o is its rest mass, B is the strength of the magnetic field and γ is the relativistic mass factor. In the gyrotron electrons are generated by an electron gun, and a sorrounding gun magnet controls the beam trajectory. The electron beam is then compressed by a main magnet as it moves through an interaction cavity. The beam then moves into the beam collection area, dissipating on the cooled walls. Finally the beam passes into the output waveguide and window, from where it is conveyed to the antenna.

Specifications for one of the three gyrotrons considered in this study - the VGA - 8003, provided to us by Varian, are given in the next few pages. The details provided there give an idea of the operational requirements and the complexity that would be involved in tailoring its design for space operation. The cooling requirements are complex and changes would have to be made to ensure operation in the severe vacuum environment of the moon, where pumps based on pressure differentials would not work, and radiation would be the only heat dissipation mechanism.

Based on the data provided to us by Varian, we have determined the scaling of the mass, volume and costs of the gyrotrons with power level. Simple interpolation was used, and the results are shown in figures 5 - 7.

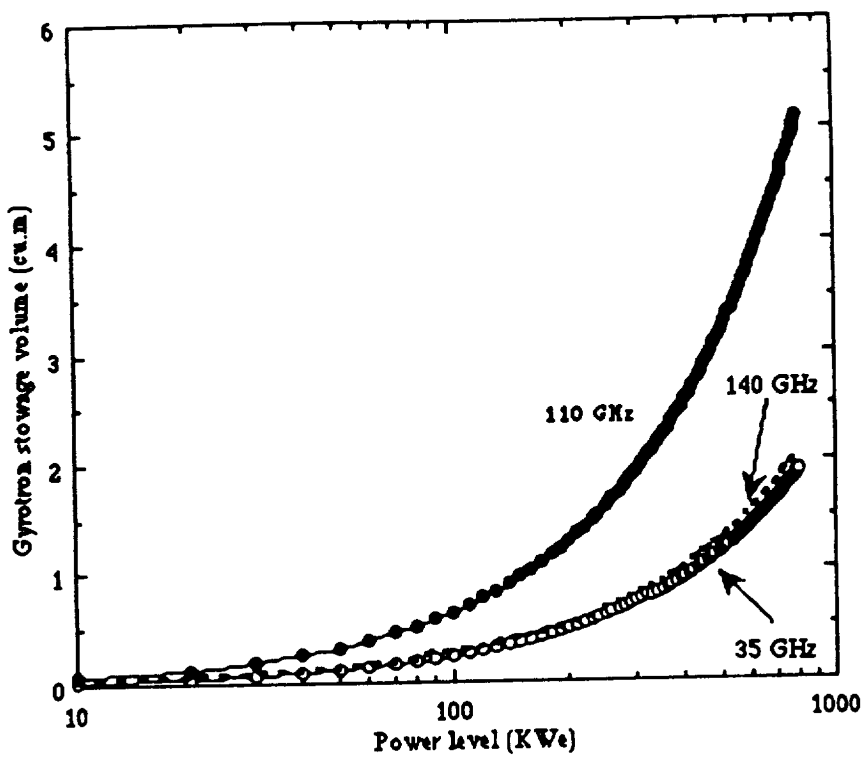


Figure 6 : Shows the scaling of gyrotron volumes with power level. This scaling was performed using data provided by Varian.

SPECIFICATIONS

TYPE VGA-8003 GYROTRON OSCILLATOR

The VGA-8003 is a cyclotron resonance interaction oscillator. The tube produces 200 kilowatts of CW power output at 35 GHz. It is liquid cooled and solenoid focused.

I. Electrical Operating Parameters

Electrical Operating Parameters	Minimum	Maximum	Typical	
Frequency	34.5	35.5	35.0	GHz
Beam Voltage	70	90	85	kV
Beam Current	4	10	7	A
Collector Dissipation	--	700	595	kW
Gun Control Anode (with respect to cathode)	14	30	26	kV
Heater Voltage (AC)	6	15	8.5	V
Heater Current	1	5	3.5	A
Heater Power	10	75	30	W
Body Current	--	50	10	mA
Gun Anode Current	--	10	2	mA
Power Output (TE_{01})	40	200	*	
Efficiency (at max power output)	30%	--	40	%

II. Power Output Sensitivities

Gun Control Anode Voltage	TBD dB/%
Main Magnet Current	TBD dB/%
Gun Magent Current	TBD dB/%
Heater Voltage	TBD dB/%
Beam Voltage	TBD dB/%

* The power can be varied in a smooth and reliable manner by variation of the gun anode voltage.

III. Beam Current Control

The operating beam current is controlled by varying the heater power. Either programming of heater voltage or servo control with beam current sensing is recommended to maintain constant beam current for long (>100 msec) pulses. The heater time constant for beam current control is 30 - 60 sec. For pulse durations between 100 msec and 30 sec a step in heater voltage coincident with the beam pulse gives approximately constant beam current. The heater voltage pulse amplitude will vary from tube to tube with a magnitude of the order of 1 to 3 volts.

IV. MAGNETIC FIELD REQUIREMENTS

The gyrotron requires an average magnetic field of 13.5 kg with shaping of the field which can require peak fields as high as 20 kg for maximum gyrotron efficiency. The magnetic fields can be supplied with the Varian magnet assembly VYW-8060L. The detailed specifications of these magnets are given in specification number A195452, and the magnet maximum field value is 35 kg. The main magnet has two main windings which provide the cyclotron resonance field for the gyrotron and other windings for gun control and beam steering. The power supples needed are furnished as a part of the magnet system. Power input requirements are 115 Vac, 40 A. The superconducting coils require liquid helium to be supplied at a rate of about 1ℓ/hr and liquid nitrogen at a rate of 0.5 ℓ/hr. To profile the beam in the collector a large water-cooled coil is used. The coil requires 26A at 125 Vdc with 1-2 gpm of cooling water. In addition, two air-cooled coils are used. These coils require two separate power supplies rated at 3A and 15 Vdc.

V. Cooling Requirements

Deionized water cooling is required as follows:

	Flow Rate gpm	Pressure Drop psi
Tube Collector	200 - 250	120 - 160
Tube Body	15 - 20	50 - 100
Output Water Load	80 - 100	15 - 30

The cathode end of the tube is designed to be operated in oil for both voltage holdoff and cooling. An oil flow of 0.3 gpm or more at 5 psi is required to cool the gun. A small submersible oil pump is recommended to supply this flow.

The output window requires FC-75 cooling of 7 to 9 gpm with a differential pressure of 20 to 30 psi. Absolute input pressure at the window should never exceed 40 psig.

VI. Load Mismatch

If mismatches are present in the 2.5 inch output waveguide a reduction in power output can be expected. VSWR's, as defined by power reflection, of 1.5:1 and 2:1 result in power reductions of 10% and 30% respectively. Some adjustment in operating parameters may be required to optimize the output in the presence of mismatches.

VII. Mechanical Parameters

Size and Weight

Tube - The tube is approximately 105 inches long and 16 inches in diameter. The weight is approximately 500 pounds.

Magnet - The magnet and socket assembly VYW-8060L is 28.5 inches in diameter. It extends 15 inches below the mounting plate and 18.5 inches above. There is a projection on one side for adding liquid helium and nitrogen which extends upward an additional 16 inches and radially outward and additional 17 inches. The magnet weight is 600 lbs.

Operating Position

The tube is designed to operate with its axis vertical and the gun end down. The output waveguide comes out vertically at the top of the tube.

Output Waveguide

The output power is in the TE^{o}_{01} mode with less than 10% of the power in other modes. The output guide is 2.5 inch ID pipe. Power distribution of the output power is best handled with 2.5 inch ID or larger pipe.

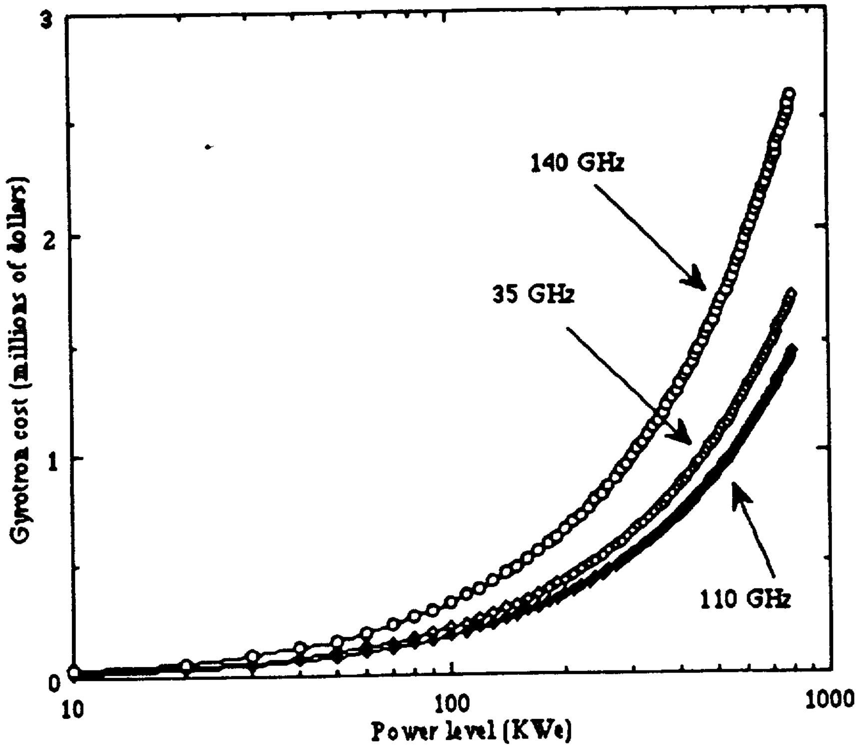


Figure 7 : Shows the scaling of gyrotron costs with power level. This scaling was performed using data provided by Varian.

Power conditioning is necessary in order to have a suitable power supply for the RF generators. As shown in the specifications for the VGA - 8003, anywhere between 85 - 100 KV high voltage AC power will have to be supplied to them. If AC power supplies are used, then a standard step up transformer for stepping up voltages can be used. Gyrotrons can also be run of high voltage DC power supplies, and in this case a DC - DC converter will have to be used. We undertook a survey to assess the status of power conditioning for space power applications. Most of the Space Station power supply is being developed at 20 KHz and number quoted for AC power management and distribution (PMAD) systems is around 110 Kg/KWe, while for a secondary DC system it is about 160 Kg/KWe (Such a system includes cables). However these numbers cannot be used in this study as the sole function of a power conditioning device in the beam power system is for voltage increments and decreases.

Resonant mode converters (a type of a DC - DC converter) are under development for space station applications at LeRC, and a number of 3.7 Kg KW was quoted to us, for this device [16]. However, since the design of this device is in its preliminary stage, we felt it was not an appropriate number to be used. Studies for SDI including the Space Power Architecture Study (SPAS) and other [17,18] studies quote 0.41 Kg/KW for DC-DC converters and since this is widely used, we have used this in our study also. Volumes and cost data for DC-DC converters are not available, but an efficiency of 92 % has been quoted which we have used. We contacted several manufactures of DC-DC converters, but it became apparent that these devices were not available at the power level and voltage required for this study, even for terrestrial applications. However it did appear that for specialized applications like the AMTRC 170 Troposcatter radio terminal and for electric traction purposes converters were custom built and the data for these devices must obtained [19].

Power conditioning for high power space applications is an area that is only recently being investigated. Summary of the work done by Canadian Astronautics Limited (CAL) in this area is pertinent to this study and has been summarized below [20]. CAL's designs are conceptual because of which the data from their study could not be used for our purposes. Resonant mode converters appear to be the most attractive candidate for space power systems since they offer high reliability, are very efficient, the electromagnetic interference (EMI) from them is low and they have low mass and volumes. For DC/AC inverters, pulse width modulated control based on MOS controlled thyristor (MCT) are the preferred candidates for high frequency and power uses. Parallel resonant inverters are suited for short circuit control, hybrid inverters are advantageous in pulse power applications and series - parallel inverters are applicable in situations where the ratio of peak to average power is low. Series and series - parallel DC - DC converters are better than parallel resonant converters. Series converters are applicable to most systems, except where high current and low voltages are required, for which the series - parallel systems can be used.

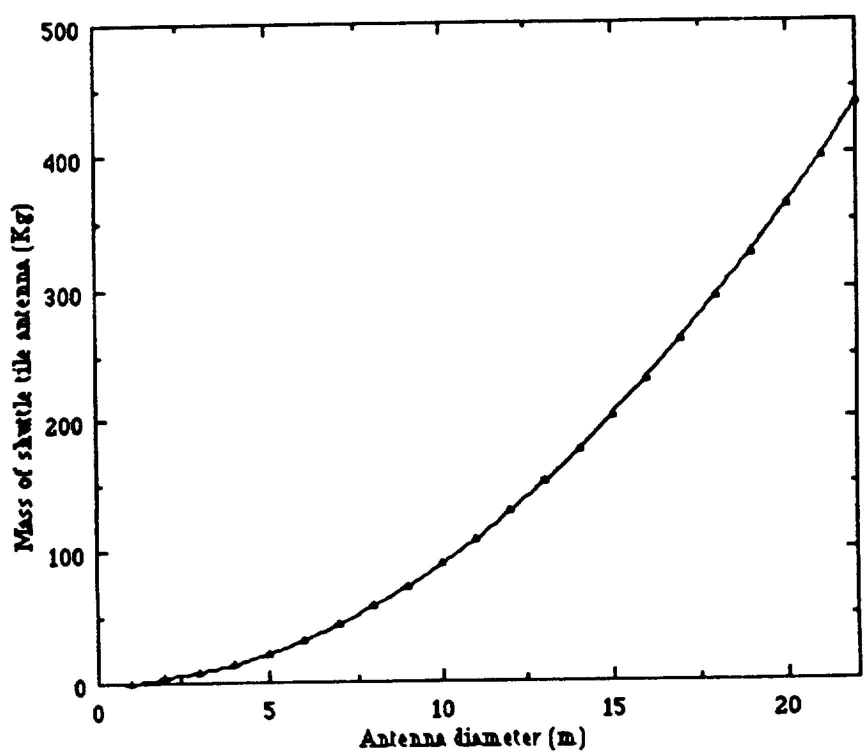


Figure 8: Variation of shuttle tile antenna mass with diameter.

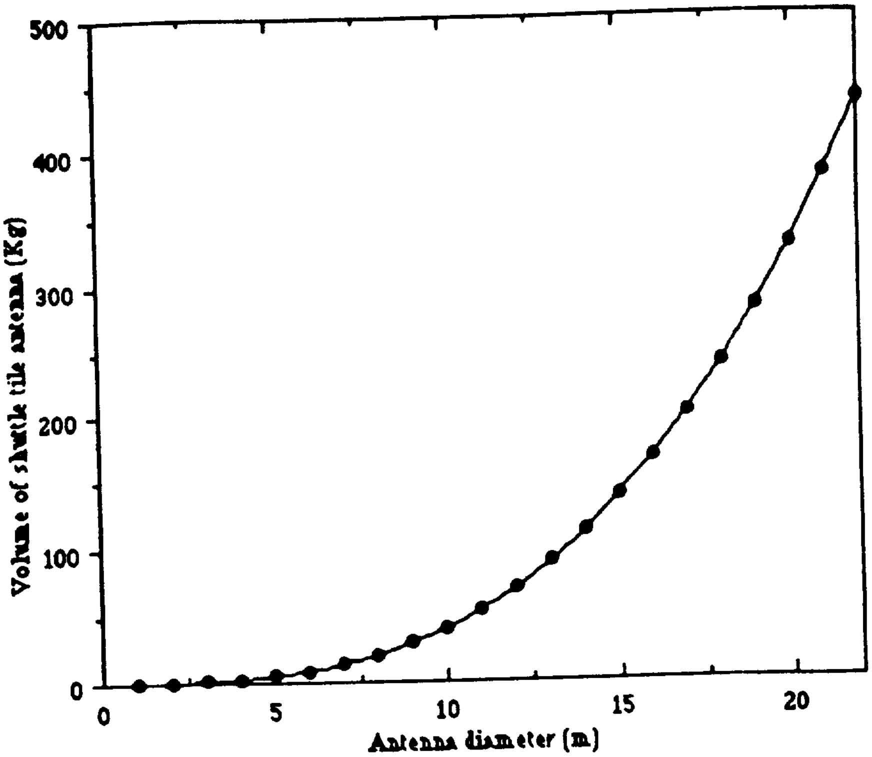


Figure 9: Variation of shuttle tile antenna volume with diameter.

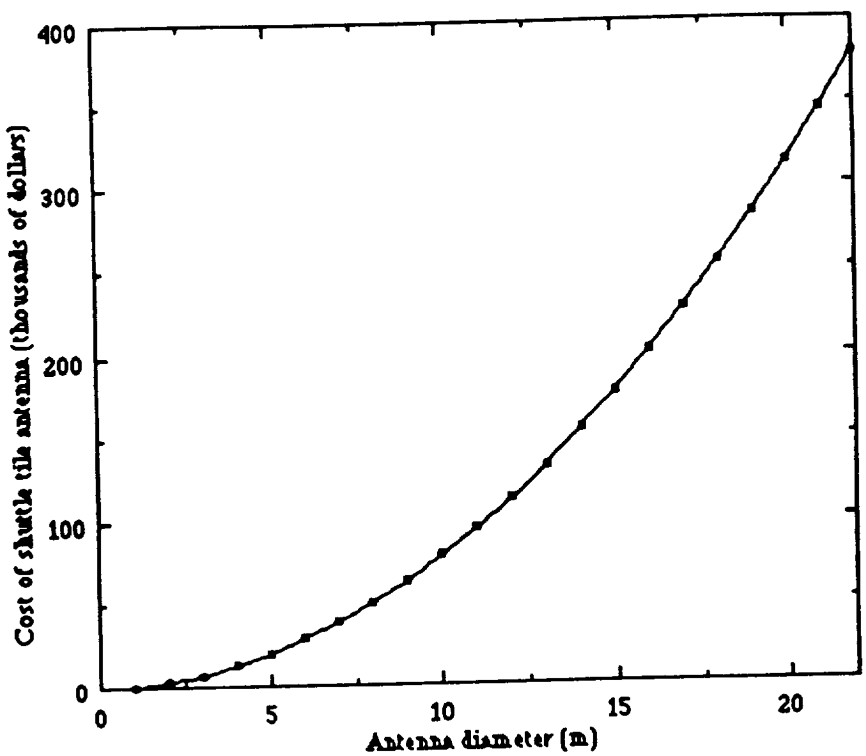


Figure 10: Variation of shuttle tile antenna costs with diameter.

The antenna system can be either a phased array or a parabolic dish. It is difficult to build phased arrays at frequencies above 30 GHz because of the limitation that the minimum distance necessary between the elements in a phased array is λ/D_t to avoid grating lobes, and as λ gets small the physical distance becomes very small. For the parabolic dishes at high frequencies, the mechanical tolerances that will have to be achieved are significant. Several kinds of such parabolic dish antennas are available, such as electrostatic membrane antennas (EMA), wrap rib antennas, inflatable antennas and simple metallic reflectors. From the view point of mass savings, inflatables are the best, followed by EMA's. The lunar base application however demands a system with long life and durability, which precludes choice of inflatables. Further inflatable technology is at a preliminary state of development due to which data could not be obtained on it.

To achieve the precision necessary (discussed earlier) in parabolic dish antennas, EMA's can be used. Further it has a low mass and can be stored in a configuration which has a low volume. The EMA is a combination of a metallized reflector that is supported on a rigid wrapped rib [21]. The shape of the membrane is controlled by use of bias and control voltages between the wrapped rib and the membrane. An optical laser system and an electronic beam scanning system have also been studied in this connection [21].

Preliminary studies on the EMA were done by Lockheed and it is presently under development by the Mission Research Corp (MRC) in Santa Barbara, Ca. From information provided by MRC, it appears that EMA's can be mounted on several alternative supports besides the wrapped rib. A 300 GHz EMA, constructed by MRC with an area of 1256 ft^2 weighs approximately 720 lbs. However no data could be obtained from MRC or Lockheed to scale the EMA for beam power applications. The next best antenna system is the shuttle tile antenna (STA) developed by Gregorwich at Lockheed Missiles and Space Co (LMSC) [22]. A prototype 1' diameter STA has been constructed with HDP - 16 shuttle tiles for millimeter - wave applications and weighs about one pound. HDP - 16 tile are made of amorphous silica and have a high strength to low mass ratio and can withstand thermal distortions. This STA has withstood vibration tests at 24 g rms.

We have used data from Gregorwich to scale the STA for the present study. A focus (f) to diameter (D_t) ratio of 0.6 has been used. The stowage volume is shown in figure 9, and is calculated as :

$$V_t = \frac{\Pi C D_t^2}{8}$$

where C is the depth of the dish and is given by :

$$C = \frac{D_t}{9.6}$$

The mass of the antenna is calculated using :

$$M_t = m_t \left(V_t - \frac{\Pi}{2}(C - t)(D_t - t)^2\right)$$

where m_t is the mass per unit volume and t is the thickness of the tile. The mass, volume and cost scaling for the STA are shown in figures 8 - 10.

Due to the pioneering efforts of William C. Brown (formerly at Raytheon Corp) rectenna technology at 2.45 GHz is well developed. This rectenna has thermal constraints because the diode temperature needs to be maintained below $200^{o}C$ which consequently restricts its operation to power densities between 400 and 1000 W/m^2, depending on the rate of convective cooling provided [23]. Polarization mismatch, electromagnetic interference (EMI), spurious oscillations and parametric amplification were some of the additional problems in Brown's original design. A dual polarized rectenna, designed by Canadian Research Center (CRC), solved most of these problems, except EMI. The CRC design could be operated at a power density of 1600 W/m^2at the conversion efficiency (85%) of Brown's design, but the thermal constraints still persist [24].

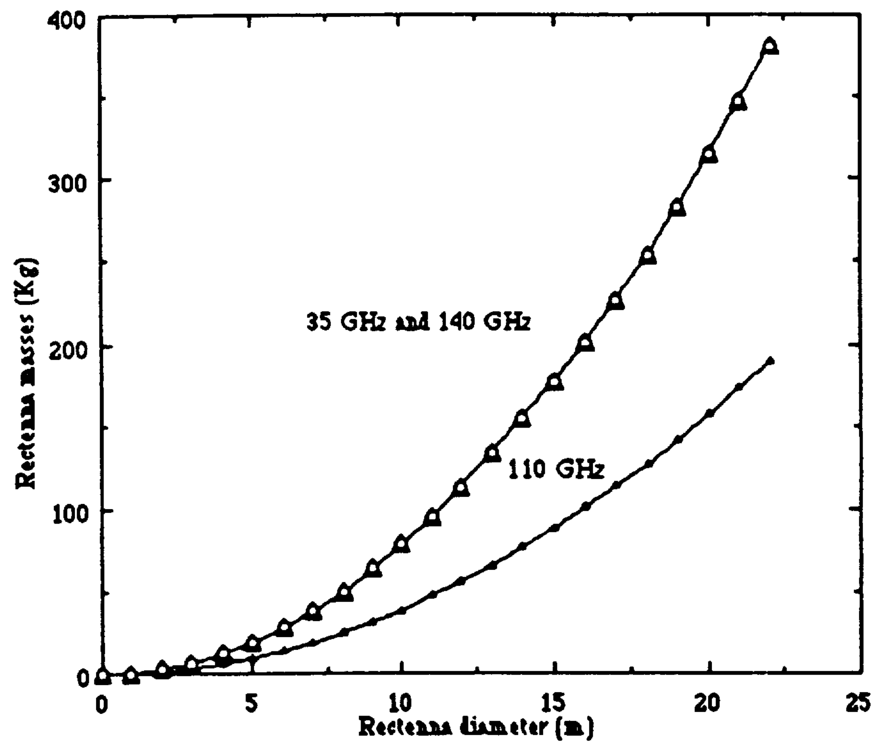


Figure 11: Variation of rectenna mass with diameter.

A preliminary design study of a 20 GHz (K - Band) rectenna was conducted by Brown [25]. A hybrid construction, using alumina substrate, silk screened circuits and beam - lead diodes was the preferred construction. It was anticipated at that time that the conversion efficiency would reduce, costs would rise sharply and convective cooling would be necessary for K band rectenna as compared to the 2.45 GHz rectenna. Follow up work on the K - band rectenna was not continued.

Rectennas have recently been built and prototypes tested at 35 GHz and there are efforts underway to build prototypes at frequencies as high as 95 GHz [26]. Rectenna development efforts at

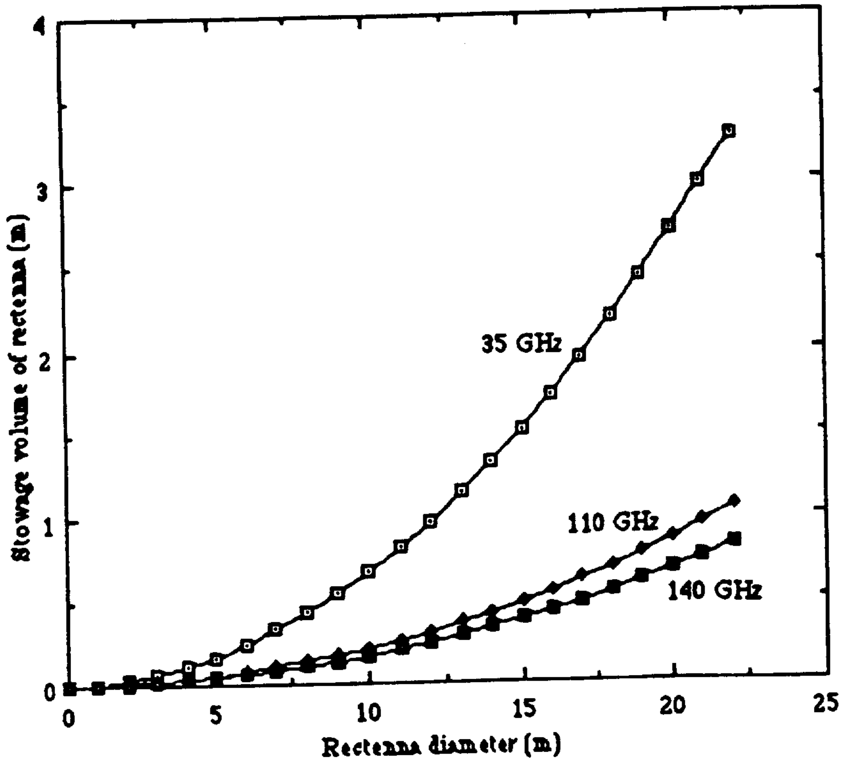


Figure 12: Variation of rectenna mass with diameter.

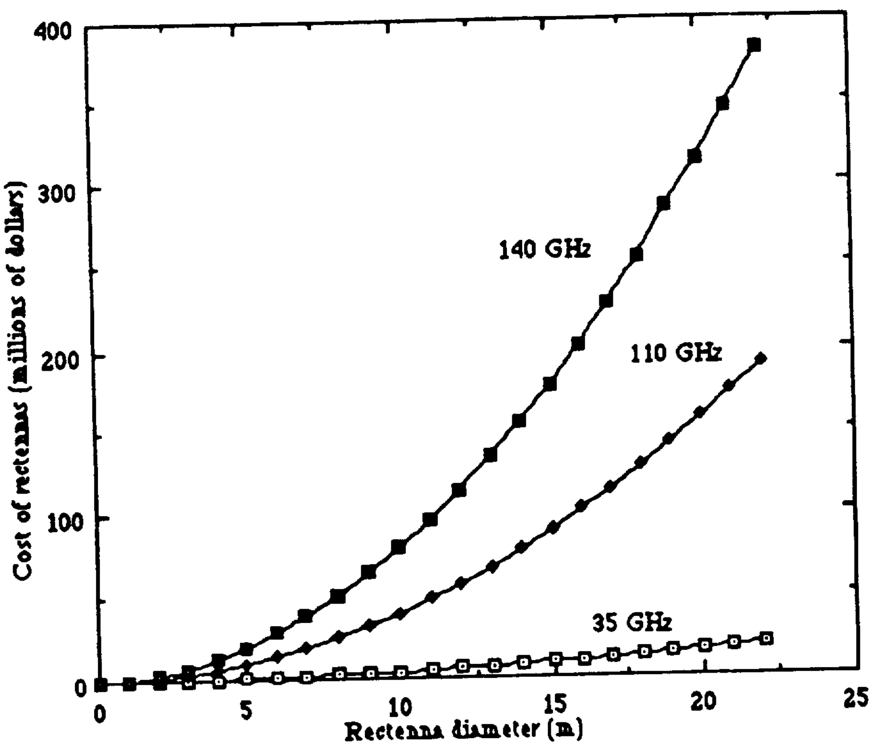


Figure 13: Variation of rectenna cost with diameter.

millimeter frequencies are continuing at Georgia Tech Research Institute and at Arco Power Technologies Inc (APTI). The APTI 35 GHz rectenna is a mm wave device built on a Duroid substrate. The major components of each element is a diode, half - wave dipole, low pass filter and a shorting capacitor. The rectenna construction is hybrid, i.e. the circuit is etched on to the substrate and diodes are bonded on to it. RF to DC conversion efficiencies as high as 70 % have been obtained and design improvements in diodes are projected to increase the system efficiency to almost 90%. This technology can have significant impact in power transmission on the lunar base. The mass, volume and cost of 35, 110 and 140 GHz rectennas as a function of rectenna diameter, were calculated by us and these results are depicted in figures 11 - 13. With light weight rectenna availability at high frequencies, hundreds of Kilowatts of power can transmitted, with a negligible mass penalty. The salient characteristics of the three beam power systems (BPS's) investigated in this study are summarized below:

Beam Power Systems considered for the Lunar base

Beam Power System 1 (BPS 1)

Frequency	35 GHz
Wavelength	8.5714 mm
Power conditioning	DC - DC converter
DC - DC converter details	
Availability	DDT & E stage
Power density	0.41 Kg / KW (SDI studies) and 3.7 Kg / KW (Space station system under development)
Efficiency	92 % (Space station system under development)
Costs	Will become available later
Stowage volume	Will become available later
DC - RF conversion	Gyrotron
Gyrotron details	
Gyrotron availability	Off the shelf - Varian Products Inc
Gyrotron #	VGA 8003
CW power	200 KW
Thermal control	Liquid cooled
Beam voltage	85 KV
Efficiency	40 %
Projected efficiency	80 %
System mass	497.73 Kg
System cost	425,000 $
System volume	0.4746 m^3
Transmit Antenna	Shuttle tile or Electrostatic membrane antenna
Antenna system details	
Antenna availability	Off the shelf - Lockheed Missiles and Space Co
Antenna type	Parabolic dish with cassegrain feeds
Shuttle tile used	HDP - 16 (Third generation tile)
Density	255.67 Kg/m^3
System Cost	3588.0 $\$/m^2$
Antenna efficiency	98 %
Scanning system	Electronic
Rectenna	Hybrid construction
Rectenna details	
Rectenna availability	Prototype (Arco Power Technologies, Inc)
Projected efficiency	95 %
Material used	Duroid substrate

Rectenna cost	50,000 $/m^2 (estimated in this study)
Rectenna mass	1.0 Kg/m^2 (estimated in this study)

Beam Power System 2 (BPS 2)

Frequency	110 GHz
Wavelength	2.73 mm
Power conditioning	DC - DC converter
DC - DC converter details	
Availability	DDT & E stage
Power density	0.41 Kg / KW (SDI studies) and 3.7 Kg / KW (Space station system under development)
Efficiency	92 % (Space station system under development)
Costs	Will become available by October '89
Stowage volume	Will become available by October '89
DC - RF conversion	Gyrotron
Gyrotron details	
Gyrotron availability	Off the shelf - Varian Products Inc
Gyrotron #	VGT - 8011
Power	500 KW CW
Thermal control	Liquid cooled
Beam voltage	85 KV
Efficiency	25 %
System mass	680.39 Kg
System cost	900,000 $
System volume	0.1875 m^3
Transmit Antenna	Shuttle tile or Electrostatic membrane antenna
Antenna system details	
Antenna availability	Off the shelf - Lockheed Missiles and Space Co
Antenna type	Parabolic dish with cassegrain feeds
Shuttle tile used	HDP - 16 (Third generation tile)
Density	255.67 Kg/m^3
System Cost	3588.0 $/m^2
Antenna efficiency	98 %
Scanning system	Electronic
Rectenna	Hybrid construction
Rectenna details	
Rectenna availability	Very early stage of development
Projected efficiency	95 %
Material used	Duroid
Rectenna cost	500,000 $/m^2 (estimated in this study)
Rectenna mass	0.5 Kg/m^2 (estimated in this study)

Beam Power System 3 (BPS 3)

Frequency	140 GHz
Wavelength	2.1429 mm
Power conditioning	DC - DC converter
DC - DC converter details	
Availability	DDT & E stage
Power density	0.41 Kg / KW (SDI studies) and 3.7 Kg / KW (Space station system under development)
Efficiency	92 % (Space station system under development)
Costs	Will become available later
Stowage volume	Will become available later
DC - RF conversion	Gyrotron

Gyrotron details	
Gyrotron availability	Off the shelf - Varian Products Inc
Gyrotron #	VGT 8014
CW power	200 KW
Thermal control	Liquid cooled
Beam voltage	85 KV
Efficiency	25 %
Projected efficiency	64.56 %
System mass	497.73 Kg
System cost	650,000 $
System volume	0.51140 m^3
Transmit Antenna	Shuttle tile or Electrostatic membrane antenna
Antenna system details	
Antenna availability	Off the shelf - Lockheed Missiles and Space Co
Antenna type	Parabolic dish with cassegrain feeds
Shuttle tile used	HDP - 16 (Third generation tile)
Density	255.67 Kg/m^3
System Cost	3588.0 $\$/m^2$
Antenna efficiency	98 %
Scanning system	Electronic
Rectenna	Monolithic Integrated Circuit Fabrication
Rectenna details	
Rectenna availability	Very early stage of development
Projected efficiency	95 %
Material used	Duroid
Rectenna cost	1000000 $\$/m^2$ (estimated in this study)
Rectenna mass	1.0 Kg/m^2 (estimated in this study)

4. SYSTEMS ANALYSIS AND FIGURE OF MERIT :

The methodology for calculating the system characteristics are now described. For any given output power level P_o and range h, the rectenna diameter D_r is first determined. The reception efficiency is fixed at 90%, which fixes the power link parameter at 1.4 (See Appendix). From examining the scaling of antenna and rectenna masses with their respective diameters, it was concluded that in order to minimize system masses and to ensure a fair intercomparison between the three BPS's, the antenna diameter must be fixed at a reasonably low value. A value of D_t = 4.0, was fixed consistent with the necessity of accommodating a rigid structure such as the STA in the shuttle bay. Consequently, the rectenna diameter can be calculated as :

$$D_r = \frac{\lambda h \chi}{D_t}$$

Once the rectenna diameter is calculated the mass, volume and costs of the rectenna can be calculated as they scale with the diameter and such scaling is discussed in section 3. The efficiency projections of Kai Chang et al [27] have been used for the conversion efficiencies of both

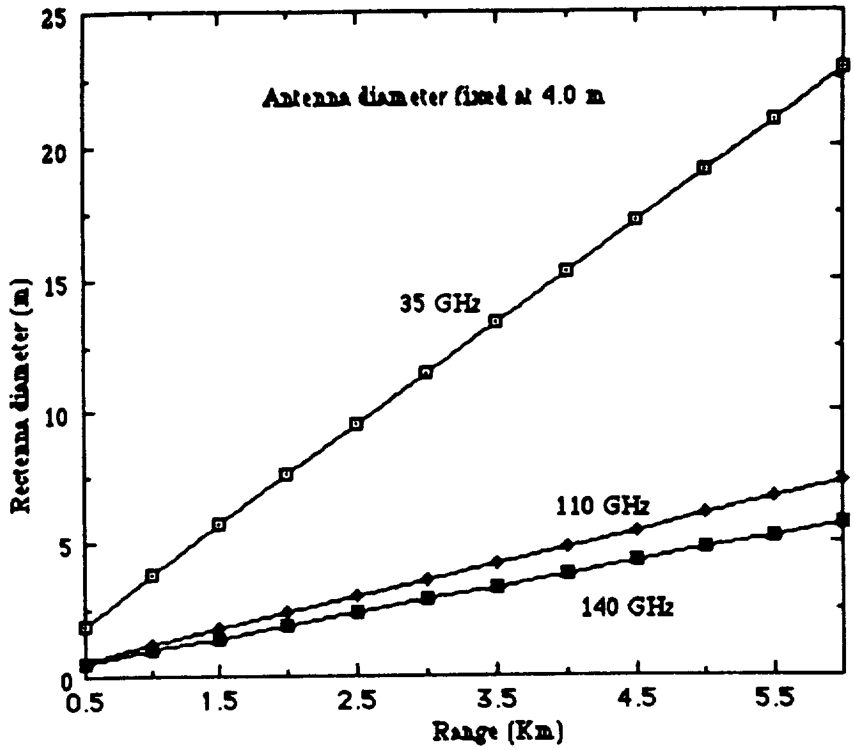


Figure 14: Variation of rectenna diameter with range based on the power transmission model developed in this study (See appendix).

gyrotrons and rectennas. Efficiency of DC to RF (RF generators or gyrotrons) is given by :

$$\eta_{dr} = -a\,f + b$$

and the efficiency of RF to DC or rectenna conversion efficiency is given by:

$$\eta_{rd} = -a\,f + c$$

where a = 1.4706 x 10^{-12}, b = 0.8515 and c = 0.8015 and f is the frequency. Projections of efficiencies along with actual efficiencies of Varian gyrotrons and the Arco rectenna are shown in figure 15. Rectenna efficiency decreases with frequency because the diode rectification efficiencies decrease with the frequency and skin losses increase by the square root of the frequency scaling factor $\sqrt{\left(\frac{f}{f_r}\right)}$

The power levels handled by the gyrotron P_g is:

$$P_g = \frac{P_0}{\eta_{rd}\,\eta_{dr}\,\eta_r\,\eta_a}$$

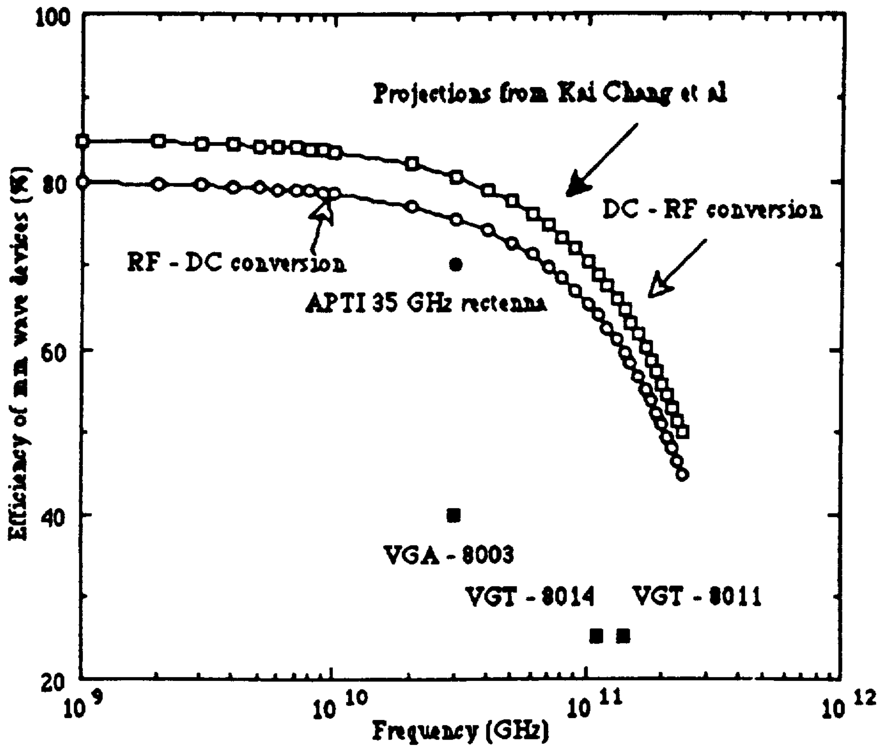


Figure 15: Projections of rectenna and gyrotron efficiencies from Kai Chang et al [26] along with data for Varian gyrotrons and the Arco 35 GHz rectenna shown as a function of frequency.

where is the η_r reception efficiency and η_a is the transmitter efficiency. It must be noted that since RF-DC and DC-RF efficiencies are a function of frequency and this must be an independent parameter in the calculation. Once the power handled by the gyrotron is calculated, the mass, volume and costs of the gyrotron can be scaled by the power level as discussed in section 3. The power handled by the DC - DC converter is:

$$P_d = \frac{P_g}{\eta_d}$$

where η_d is the efficiency of the DC - DC converter. Consequently the mass of the device is calculated. Since antenna diameter is fixed in this calculation, its volume, cost and mass can be calculated as :

$$V_t = \frac{\Pi C D_t^2}{8}$$

where C is the depth of the dish and is given by :

$$C = \frac{D_t}{9.6}$$

The mass of the antenna is calculated using :

$$M_t = m_t \left(V_t - \frac{\Pi}{2}(C - t)(D_t - t)^2\right)$$

A tower is necessary for the antenna and the rectenna to be physically in view of on another. It has been suggested that full advantage of the topography be taken on the moon to situate the antennas

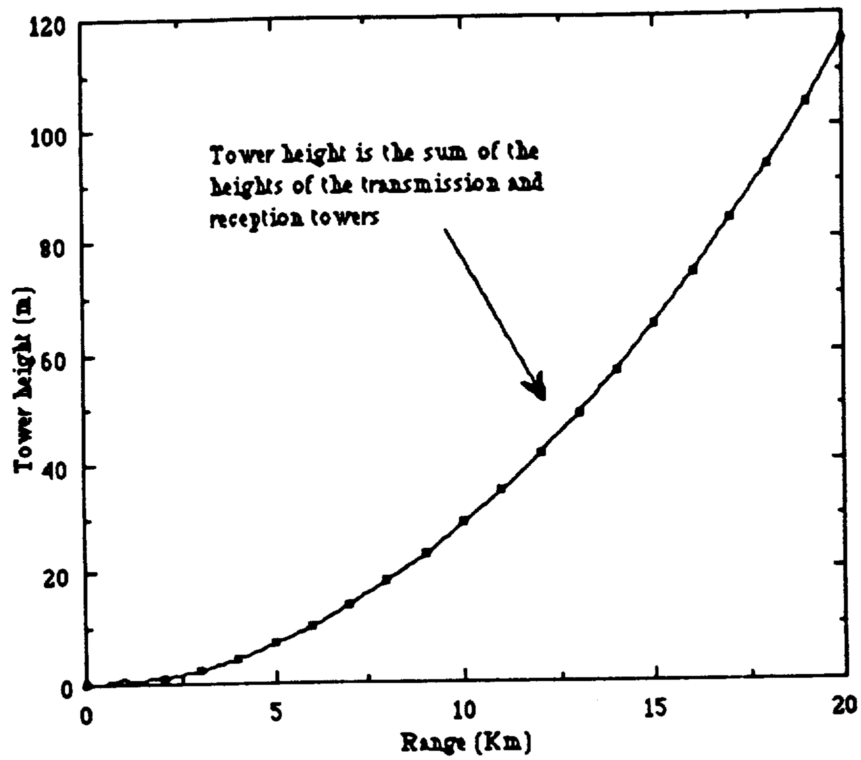


Figure 16: Tower heights necessary to deploy a beam power system on the moon as a function of the range.

on hills. The reception tower could also be integrated on the roofs of structures, which would prevent the necessity of building towers. The tower height necessary for the BPS on the moon is calculated as a function of the range and is depicted in figure 16. (The tower height is the sum of the towers at the transmitter and receiver end) The system masses are calculated by adding the masses of the component subsystems and similarly are the volumes and costs. Contour plots of the mass, volume and costs for output power levels from ≈ 10 KW to 800 KW, for ranges up to 6 Km (the distance between transmitter and rectenna) are shown in figures 17 -24. System mass, volume and cost does not include that of the towers. System volume and costs exclude that of DC-DC converters. System costs are procurement costs only and do not include transportation, assembly and maintenance costs.

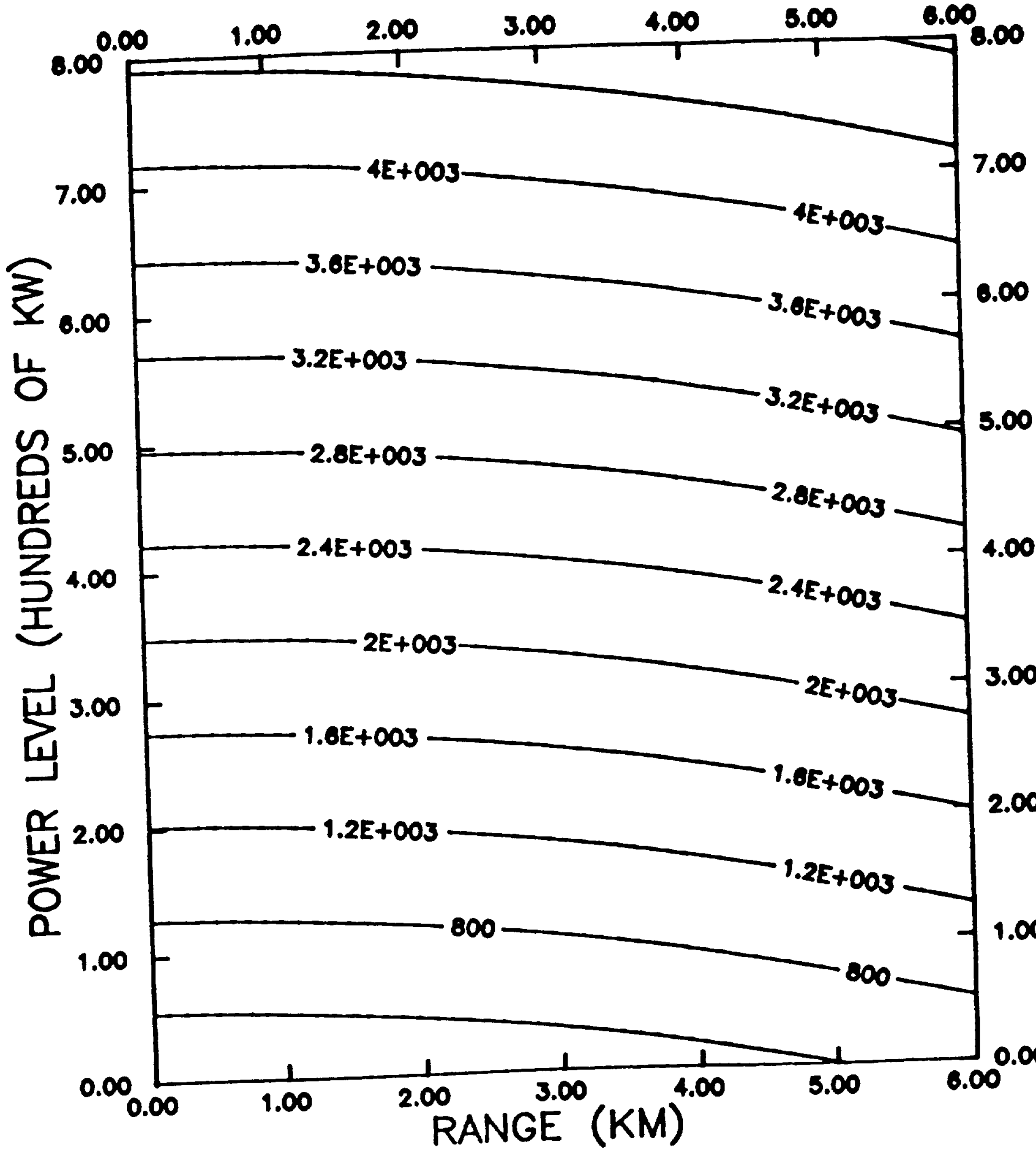


Figure 17: Contour plot of the mass of the 35 GHz beam power system as a function of range and power level.

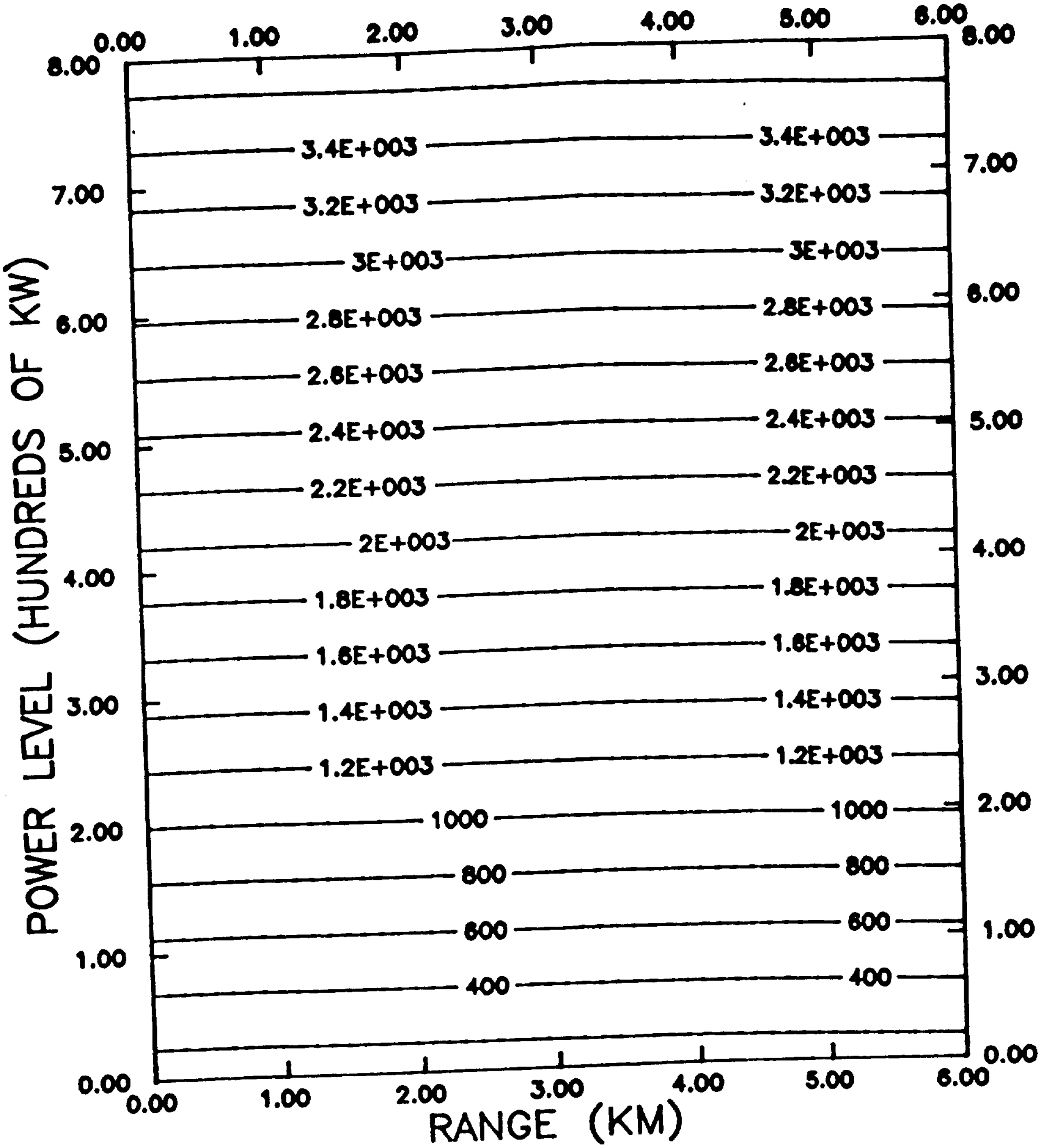


Figure 18: Contour plot of the mass of the 110 GHz beam power system as a function of range and power level.

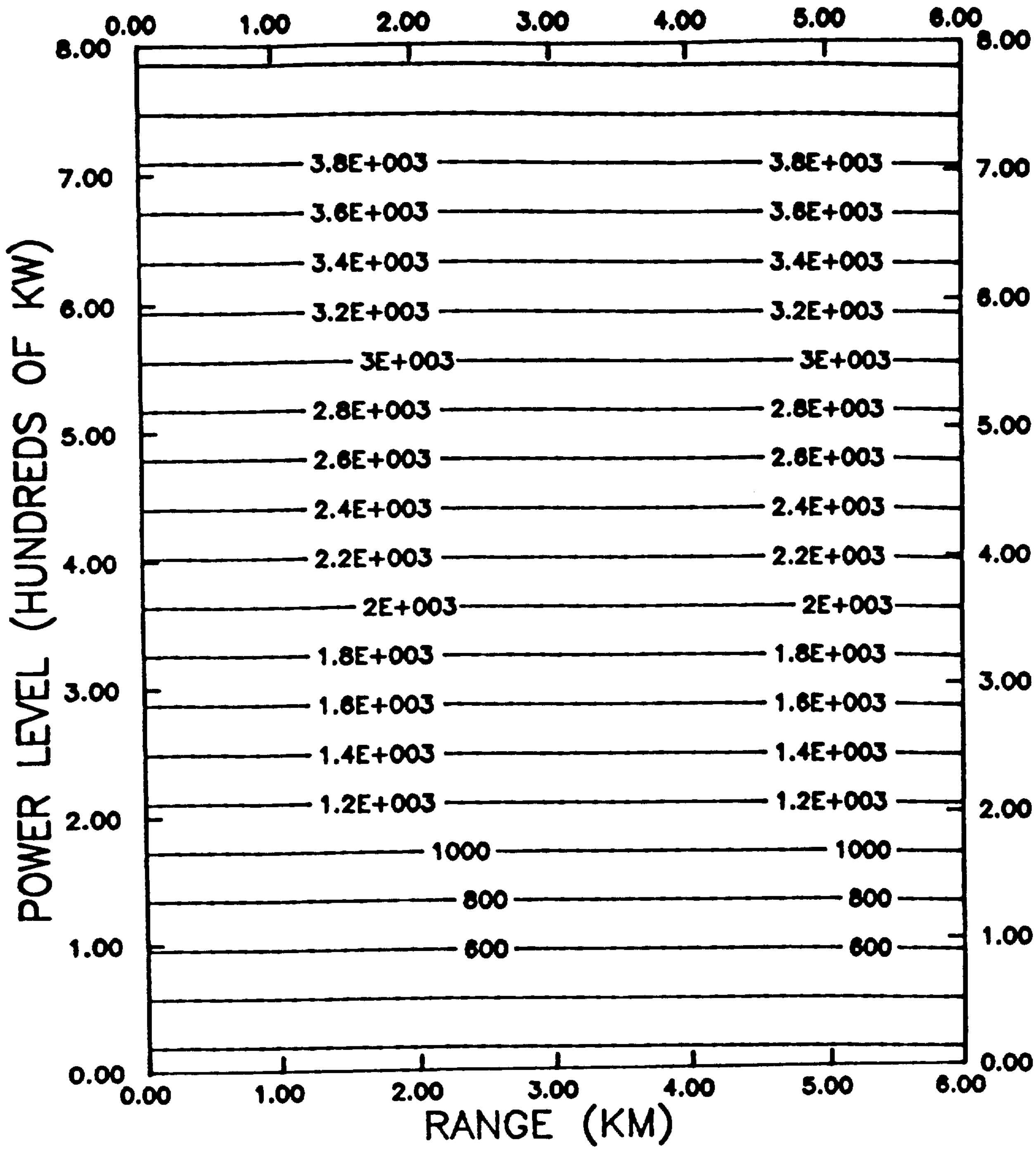


Figure 19: Contour plot of the mass of the 140 GHz beam power system as a function of range and power level.

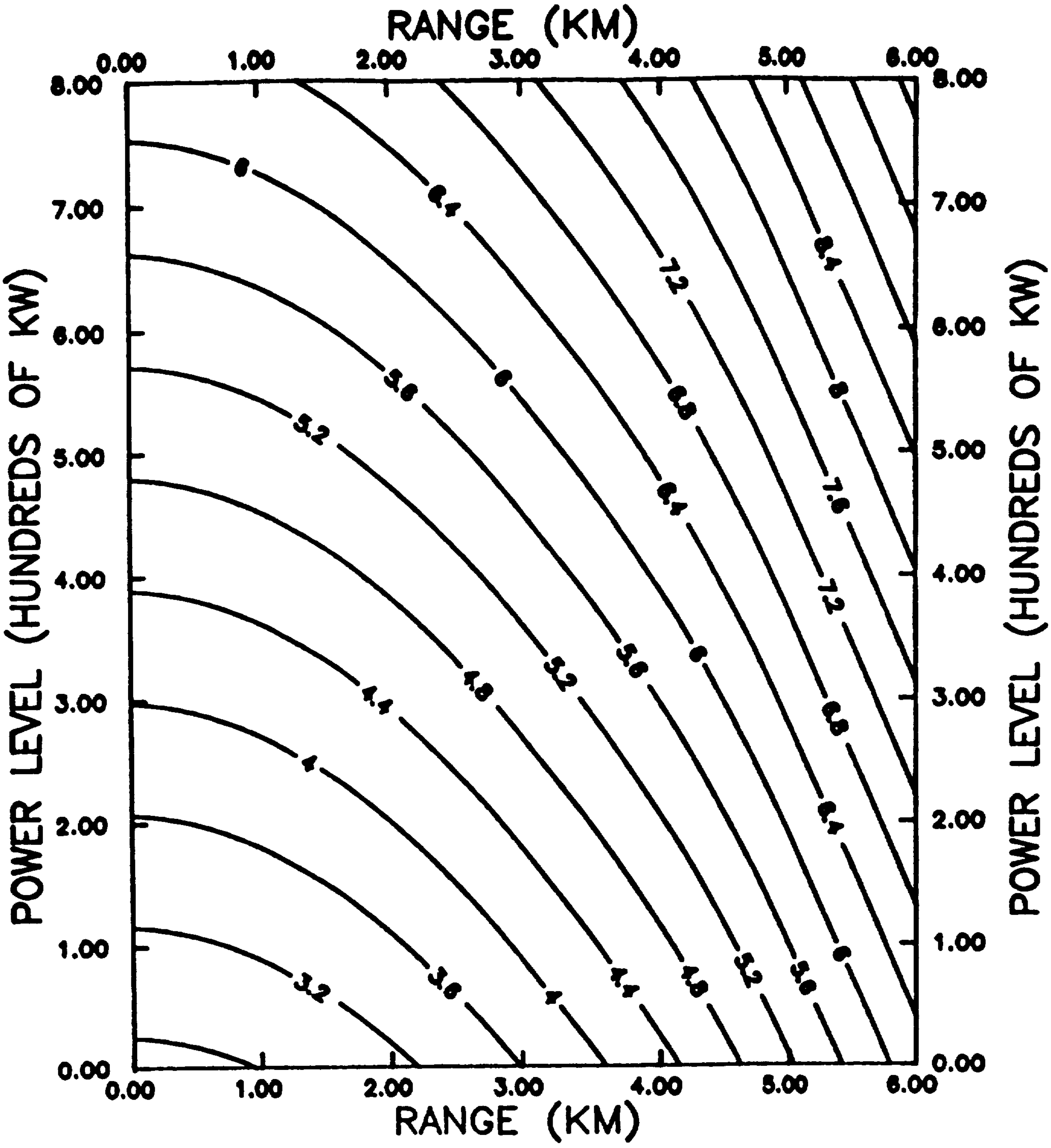


Figure 20: Contour plot of the volume of the 35 GHz beam power system as a function of range and power level.

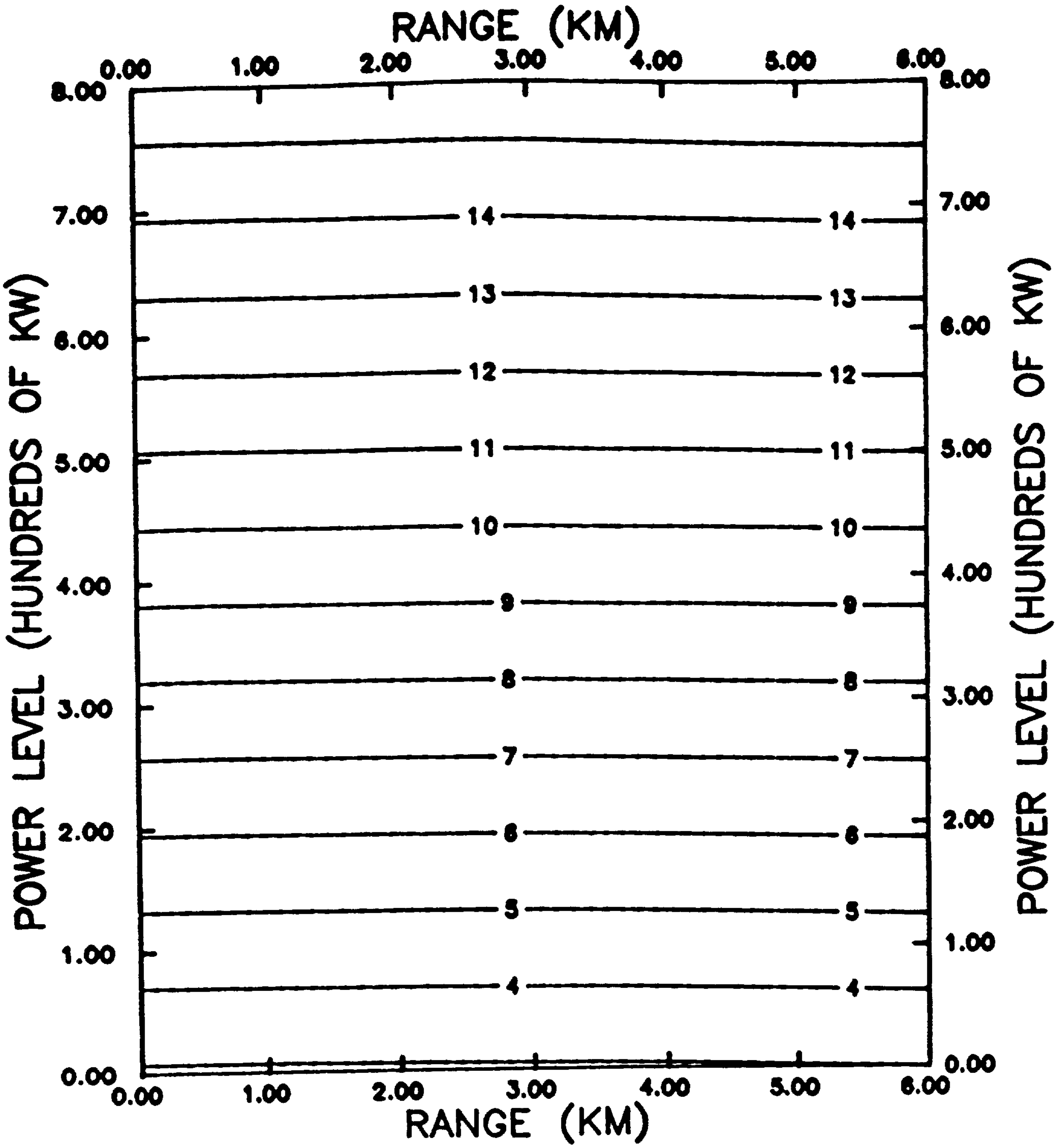


Figure 21: Contour plot of the volume of the 110 GHz beam power system as a function of range and power level.

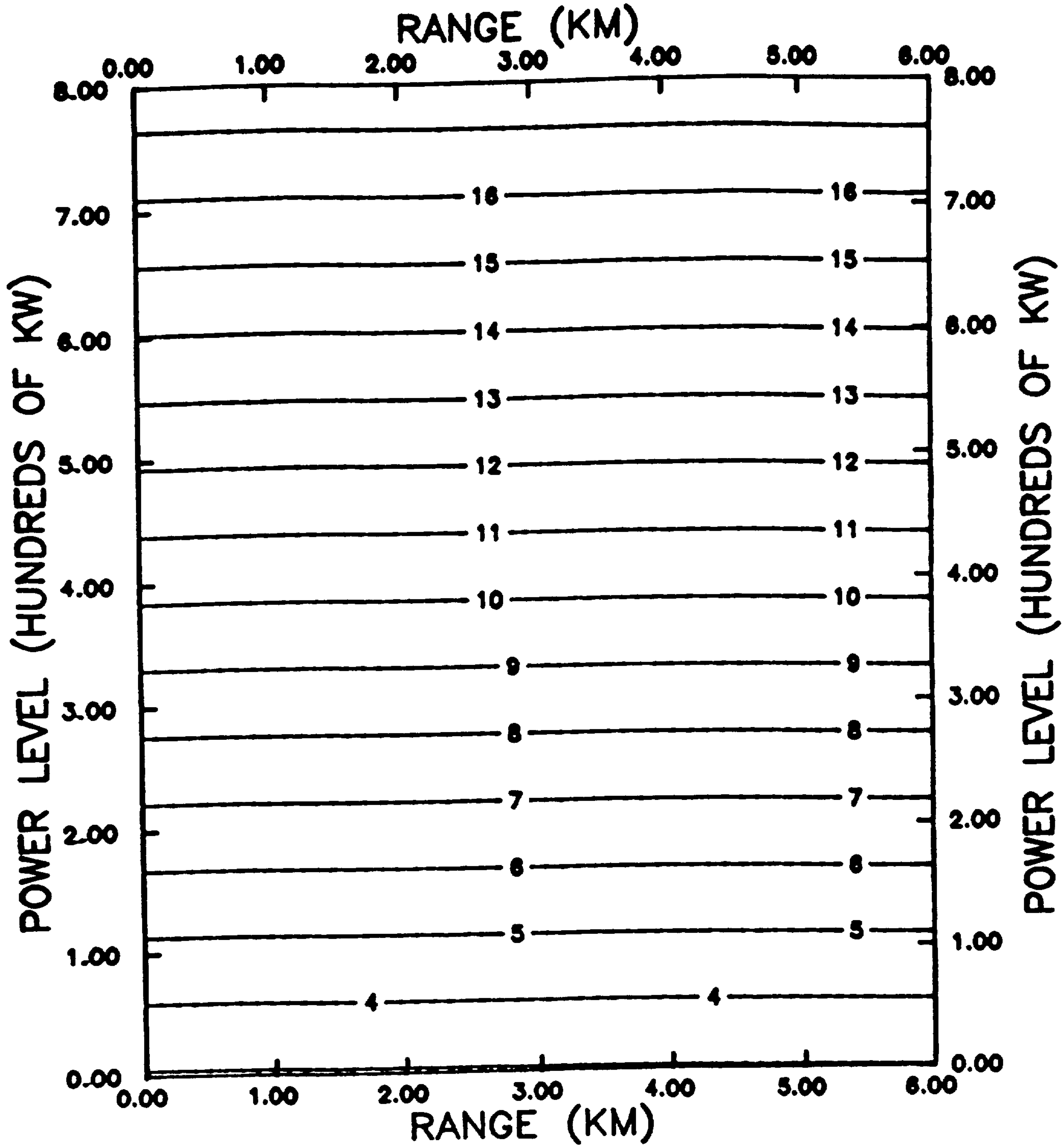


Figure 22: Contour plot of the volume of the 140 GHz beam power system as a function of range and power level.

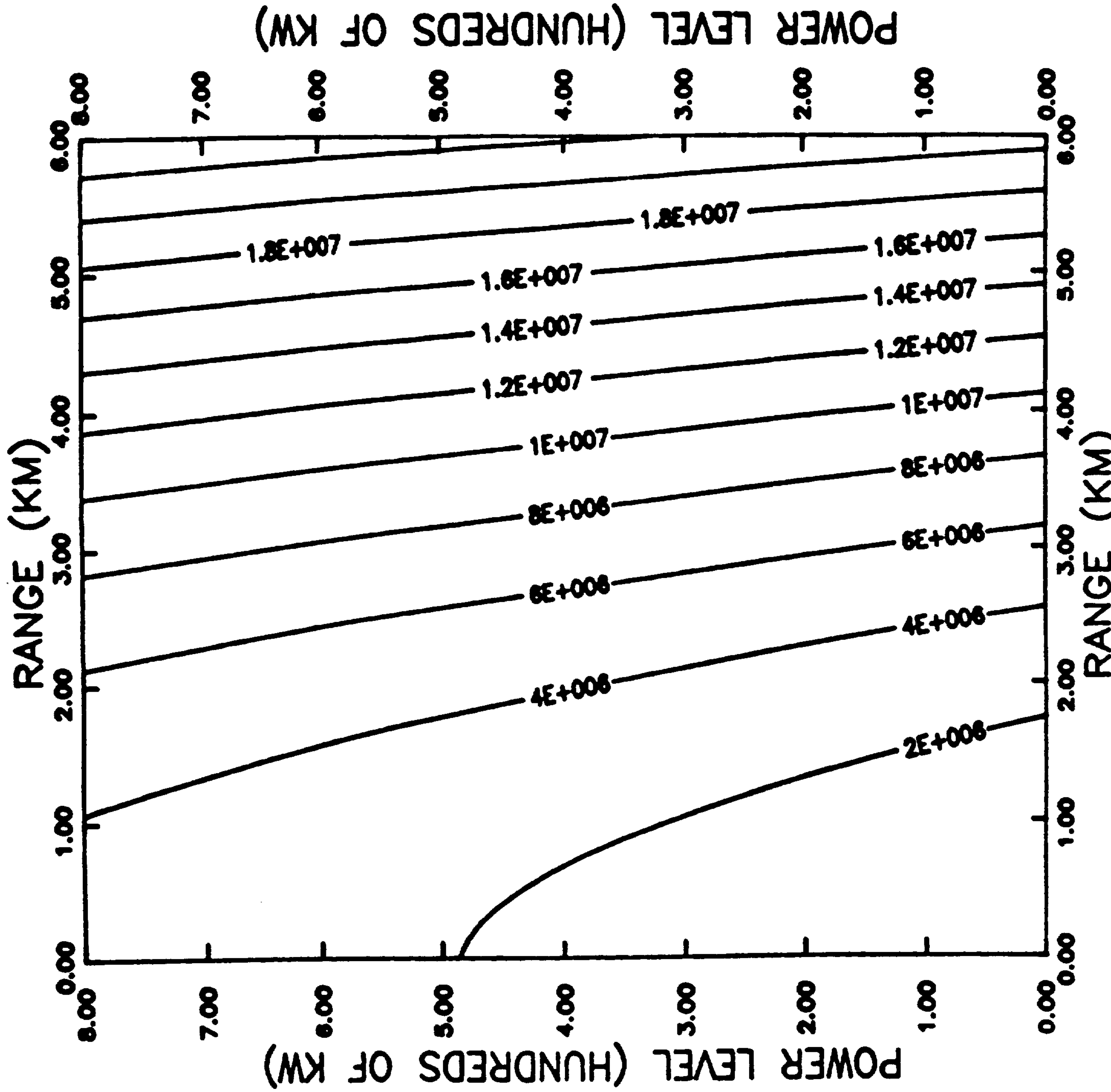


Figure 23: Contour plot of the cost of the 35 GHz beam power system as a function of range and power level.

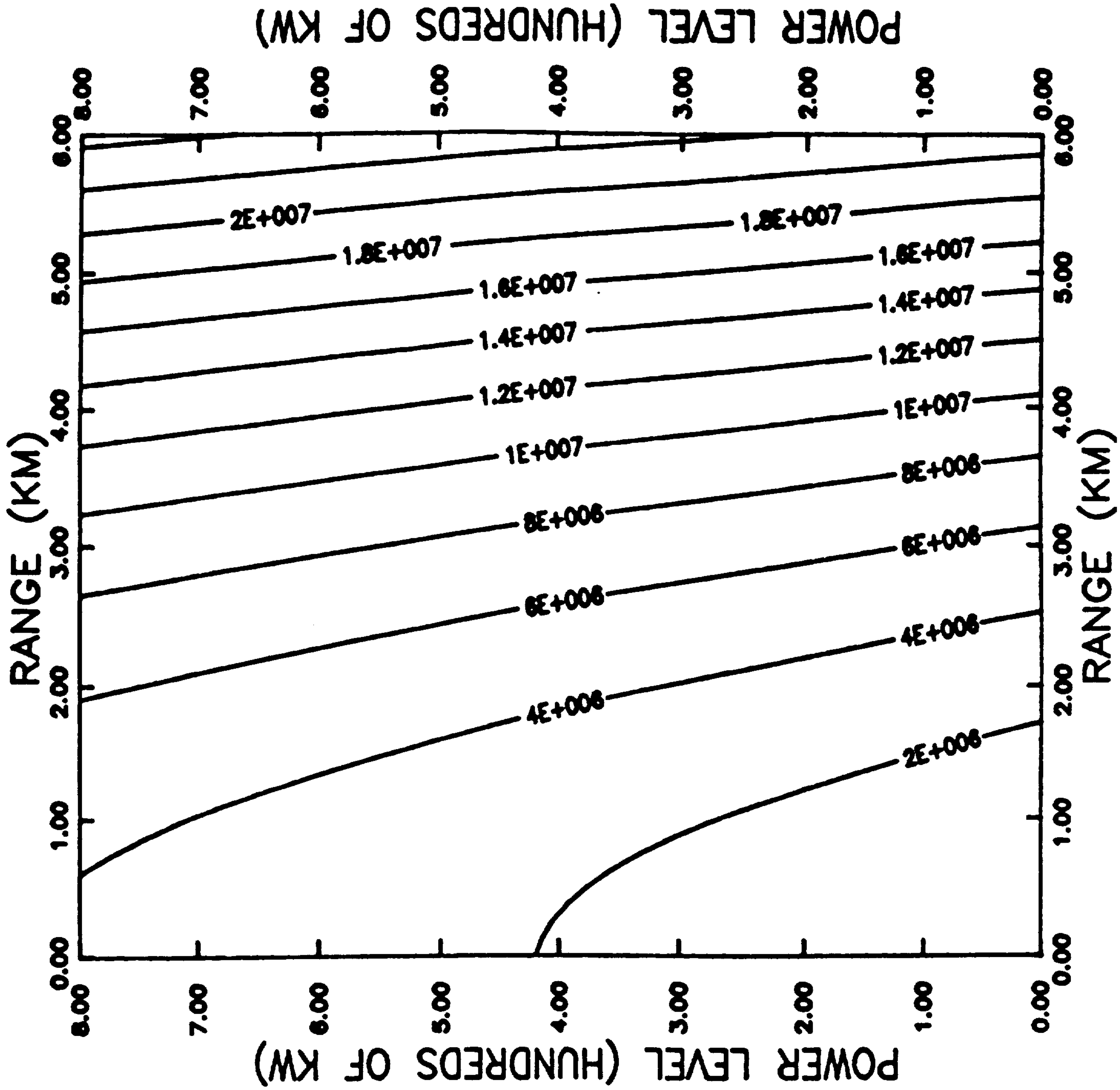


Figure 24: Contour plot of the cost of the 110 GHz beam power system as a function of range and power level.

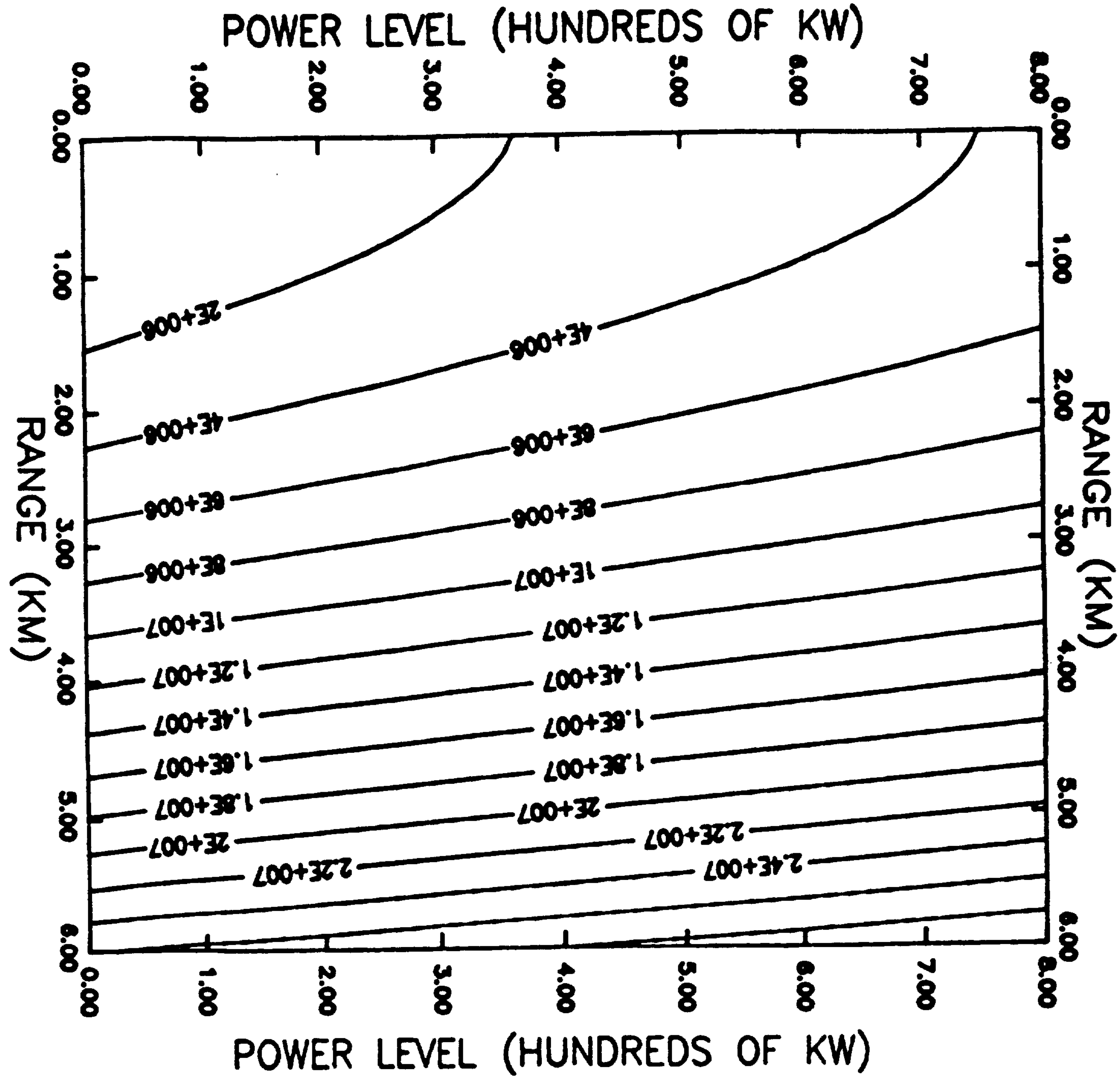


Figure 25: Contour plot of the cost of the 140 GHz beam power system as a function of range and power level.

CRITERION	WEIGHT FACTOR	RELATIVE WORTHS 35 GHz	110 GHz	140 GHz
Mass	0.25	1	3	2
Volume	0.20	3	2	1
Cost	0.10	3	2	1
Efficiency	0.20	3	2	1
Technical Maturity	0.10	3	2	2
Safety	0.05	1	2	3
Reliability	0.10	3	3	3
Totals	1.0	2.4	2.35	1.65

Table 1: The figure of merit calculation for the three beam power systems.

Table 1, shows the figure of merit calculation for the three beam power systems. The objective of this calculation is to determine the most appropriate and best means of powering a given mission / mission element. Once the power system alternatives have been ranked in an effort to simplify the selection process, suggestions for technology development can be made. Various alternative techniques to calculate the figure of merit were looked into by General Electric (GE) during the course of their SPAS study [17]. Some of the methods examined include :

Multiple - Attribute Decision Analysis Technique (MADT)
developed by Los Alamos National National Labs.

Use of commercially available "expert" systems.
Use of spreadsheet processors like EXCEL or LOTUS 1- 2 - 3.

Developing a custom code using FORTRAN or any other
high level language.

The approach GE used in the SPAS study was a menu driven, LOTUS 1- 2 - 3 spreadsheet approach. First a set of relative worth criteria that dictate selection of the power system are determined. The criteria used in this study are :

System mass

Volume

Cost

Efficiency

Technology maturity

Safety

Reliability

Weighting factors are necessary to calculate the figure of merit and were to be user supplied in the GE study. The sum of the weighting factors for a power system must equal 1. Choice of weighting factors introduces bias into the processes and has been the subject of many articles. The figure of merit is calculated as :

$$FOM = \sum_{c=1}^{n} RV_c \times WF$$

where, FOM is the figure of merit of a power system, for any given mission / mission element, RV_c is the relative worth factor of each of the criteria for a power system, WF is the weighting factor of the criteria and c is the number of criteria, and c = 7, in our study. The 35 GHz system appears to be the best system for the lunar base power transmission, followed closely by the 140 GHz system.

Christian [28] has discussed the advantages of beam power over in board continuous power (ICP) systems for mobile power (rovers and construction equipment) which are:

- increase in payload fraction
- increase in range
- increase in time utilization
- reduction in total mass to lunar surface

Some of these such as reduction in total mass to lunar surface and increased range also apply to the use of beam power for stationary power. Safety considerations due to microwave radiation will reduce acceptance of beam power systems. In spite of the fact that microwave radiation below the national standard, has shown to be a non-issue, which of course has led to the acceptance of microwave ovens. Further, protection from radiation will be anyway provided by Extra Habitat Activity (EHA) suits and habitats. Acceptability will not be an issue with regard to high voltage AC or DC cables, though emerging health concerns of the link between power lines and cancer occurrence will have to be taken into consideration.

Electromagnetic interference (EMI) of the beam power system with the communication or other electrical/electronic equipment needs to be better understood. EMI might require additional shielding to equipment which in turn will be a cost and mass driver. The costs of transporting and assembling a cable system will far outweigh that of a beam power system system. The initial system cost and the technology development costs of the beam power system will be greater than that of the cable system. Cable systems are a reliable proven technology that have existed for decades, whereas beam power technology is only proven at 2.45 GHz and higher frequency technology is a very recent development. The construction and maintenance time required for a beam power system will be less than that of cable systems. Temperature cycling on the moon will have to be addressed in the design of any power transmission system as the thermal control requirements will vary widely between day and night. Precautions against dust contamination and local radiation hazards will also have to be taken. Beam and cable transmission systems have several advantages and disadvantages with regard to their respective deployment on the lunar base. Further study needs to be conducted in order to understand all the trade - offs involved in deploying either a cable transmission system or a beam power system, including an investigation of all deployment configurations of the latter.

5. CONCLUSIONS AND RECOMMENDATIONS :

The feasibility of surface - to surface beam power transmission at millimeter wave frequencies on the lunar base has been investigated in this study. It appears that beam power is a viable scheme and a 35 GHz system should be considered for power transmission to stationary users on the moon. Table 2 shows the deployment sequence necessary to power the different users, their range and power requirement.

The parameters of the different phases of the 35 GHz beam power system for the lunar base are summarized below :

Beam Power System deployment for the Lunar base

(System volumes and costs do not include power conditioning. System masses do not include mass of towers.)

35 GHz beam power system

BPS phase	P 1
Antenna diameter	4.0 m
Rectenna diameter	21.44 m
System efficiency	48.69%
System mass	598.61Kg
System volume	5.89 m^3
System cost	18223140.0 $
Required tower height	7.15 m

BPS phase	P 2
Antenna diameter	4.0 m
Rectenna diameter	7.89 m

System efficiency	48.69%
System mass	92.54 Kg
System volume	3.06 m^3
System cost	2482602.0 $
Required tower height	1.14 m
BPS phase	P 3
Antenna diameter	4.0 m
Rectenna diameter	1.13 m
System efficiency	48.69%
System mass	349.51 Kg
System volume	2.89 m3
System cost	303454.10 $
Required tower height	negligible
BPS phase	P 4
Antenna diameter	4.0 m
Rectenna diameter	21.44 m
System efficiency	48.69%
System mass	709.51 Kg
System volume	5.98 m^3
System cost	18303450.0 $
Required tower height	7.15 m
BPS phase	P 5
Antenna diameter	4.0 m
Rectenna diameter	3.39 m
System efficiency	48.69%
System mass	412.95 Kg
System volume	3.01 m3
System cost	743609.10 $
Required tower height	0.311 m
BPS phase	P 6
Antenna diameter	4.0 m
Rectenna diameter	3.39 m
System efficiency	48.69%
System mass	579.30 Kg
System volume	3.14 m^3
System cost	864073.90 $
Required tower height	0.311 m
BPS phase	P 7
Antenna diameter	4.0 m
Rectenna diameter	25.95 m
System efficiency	48.69%
System mass	766.61 Kg
System volume	7.33 m3
System cost	26623140.0 $
Required tower height	10.36 m
BPS phase	P 8
Antenna diameter	4.0 m
Rectenna diameter	3.39 m
System efficiency	48.69%
System mass	1688.26 Kg
System volume	4.04 m^3

System cost 1667175.0 $
Required tower height 0.311 m

ID	YEAR	BPS Phase	Power Transmission and reception regions	Power Requirements day KW	Night KW	Trans-mission Range Km
I - 2	2002	P1	Power transmitted from PV/RFC to launch and landing support (Zone 4)	40	25	5
I - 5	2004	P2	Power transmitted from SP-100 T/E to ISRU (Zone 3)	5	5	2
II - 2	2005	P3	Power transmitted from SP - 100 T/E to habitat (Zone 1)	60	60	0.5
II - 2	2005	P4	Power transmitted from PV to moving construction equipment	60		5
II - 6	2009	P5	Power transmitted from SP - 100 Stirling to LOX plant (Zone 3)	70	70	1
II - 7	2010	P6	Power transmitted from SP - 100 Stirling to ISRU demo (Zone 3)	100	100	1
III - 1	2011	P7	Power transmitted from SP - 100 Stirling to launch and landing support (Zone 4)	40	25	6
III - 2	2012	P8	Power transmitted from SP - 100 Stirling to LOX plant (Zone 3)	300	300	1

Table 2 shows the deployment sequence necessary to support the different users on the lunar base. Power requirements and the range of the users in phases P1 through P8 are also shown.

The major conclusions of this study are:

- Surface - to - surface power beaming for stationary power sources at mm - wave frequencies is feasible and has several advantages.
- Power conditioning for space based high power applications is at a low level of development and impacts any system, including beam power.
- Availability of high power CW gyrotrons dictate frequency selection for beaming.
- Antenna technology, except inflatables is fairly well developed.
- High frequency rectennas are in a preliminary state of development, but recent 35 GHz

rectenna development is encouraging.

- Beam power system masses seem to scale with power level than range, with a maximum of about 4 tonnes at 800 KW delivered power.
- Beam power stowage volumes seem to scale with power level than range, with a maximum of about 17 m^3 at 800 KW delivered power.
- Beam power system costs seem to scale with range than power level, due to the costs of rectennas.
- Efficiency of the 35 GHz system is the highest (48.69 %) followed by the 110 GHz system (35.80 %). The 140 GHz system is the least efficient (31.30 %).
- Beam power systems and cable systems have relative advantages and disadvantages and further study is necessary before a selection of power transmission systems is made.

It is recommended that:

- Beam power be considered as the candidate power transmission system for NASA's lunar base.
- A comparison study between cable and beam power system for lunar base power transmission be initiated.
- The present study be extended by additional technology survey, refinements in the cost analysis and system analysis procedures.
- Beam power configurations besides surface - to surface transmission be studied.
- A figure of merit model be developed to intercompare millimeter, laser and direct power systems for NASA's space exploration missions.
- Rectenna design, development and testing at 35 GHz and higher frequencies be initiated.
- Power conditioning for space based Kilowatt and higher level systems be designed and developed.
- Theoretical and experimental studies be conducted to improve gyrotron technology.

6. APPENDIX : POWER RECEPTION EFFICIENCY ANALYSIS

A power reception efficiency analysis model formulated earlier [7, 8] for the case of microwave power transmission from earth based transmitters to orbiting satellite constellations, has been extended in this study. The model in the present format can be used to analyze the power transmission for either orbiting satellites beaming power to the surface of a planetary body / moon or for point - to - point power beaming in addition to the case mentioned above.

We assume that the transmitter is a horizontal square phased array of side D_t with $N \times N$ isotropically radiating elements uniformly spaced a distance $\ell = D_t/N$ apart. This is an idealization of the slotted waveguide radiation sources we envision as uniformly distributed over the transmitter. A reflecting backplane will probably be necessary to avoid downward power losses. By varying the input phase distribution across the array, a focussed coherent beam is produced along the boresight r_o which tracks the center of a square rectenna of side D_r. The incidence angles of rays from the transmitter aperture center on a horizontal plane are related to the zenith and azimuth angles (Θ,ϕ) of the spherical coordinate system by (see fig.26)

$$\sin\Theta_x, \sin\Theta_y = \sin\Theta\cos\phi,\ \sin\Theta\sin\phi .$$

$$\sin\Theta_{xo}, \sin\Theta_{yo} = \sin\Theta_o\cos\phi_o,\ \sin\Theta_o\sin\phi_o .$$

Assuming the phase shifts fed along each axis are independent, the diffraction-limited intensity field normalized to the boresight peak is expressible as the product of the x and y distributions (See Skolnik, [29]) :

$$\frac{I}{I_o} = \left\{\frac{E}{E_o}\right\}^2 = \left\{\frac{\sin\frac{N\Psi_x}{2}}{N\sin\frac{\Psi_x}{2}}\right\}^2 \times \left\{\frac{\sin\frac{N\Psi_y}{2}}{N\sin\frac{\Psi_y}{2}}\right\}^2 ,$$

where

$$\Psi_x \equiv k\ell(\sin\Theta\cos\phi - \sin\Theta_o\cos\phi_o) = k\ell(\sin\Theta_x - \sin\Theta_{xo}) \cong k\ell\Delta\Theta_x\cos\Theta_{xo}$$

and

$$\Psi_y \equiv k\ell(\sin\Theta\sin\phi - \sin\Theta_o\sin\phi_o) = k\ell(\sin\Theta_y - \sin\Theta_{yo}) \cong k\ell\Delta\Theta_y\cos\Theta_{yo}$$

Here $k = 2\pi/\lambda$ is the wave number, subscript zero denotes the boresight direction, and the approximations are for small angular deviations from r_o. These are the deviations in the xr and yr planes are defined by $(\Delta\Theta_x, \Delta\Theta_y) = (\Theta_x - \Theta_{xo}, \Theta_y - \Theta_{yo})$. It can be shown that $\Delta\Theta_x$, $\Delta\Theta_y$ are of order $\lambda/D_t << 1$, so the physical displacements normal to the boresight axis are $\approx$

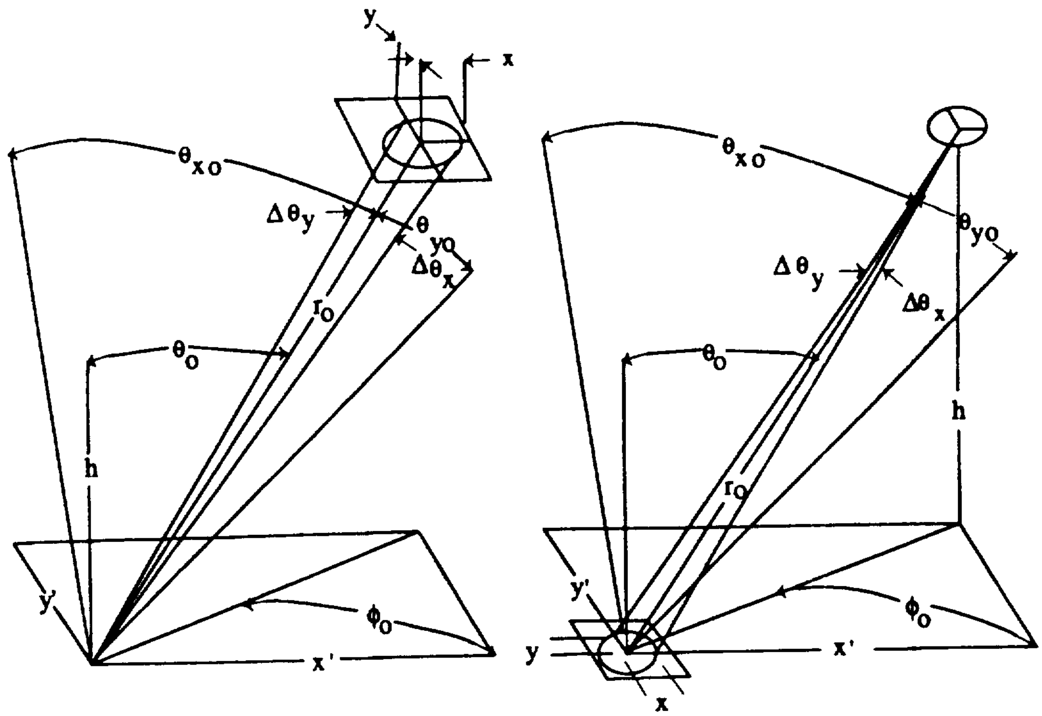


Figure 26. Geometry of horizontal transmitter and receiver during a flyby. The spherical coordinates r, Θ and ϕ are related to the Cartesian coordinates measured from the center of the transmitter by $x' = r\sin\Theta\cos\phi = r\sin\Theta_x$, $y' = r\sin\Theta\sin\phi = r\sin\Theta_y$ and $h = r\cos\Theta$, where $\Theta_x = \arcsin(x'/r)$ and $\Theta_y = \arcsin(y'/r)$ are the $\angle$'s between the $x' = 0$ and $y' = 0$ planes and the range vector r measured in the planes containing r. Subscript zero denotes the boresight direction, and $\Delta\Theta_x, \Delta\Theta_y$ are the angular deviations in the rx and ry planes from boresight.

$(r\Delta\Theta_x, r\Delta\Theta_y)$. However a consequence of the oblique projections of the beam when the boresight is at arbitrary incidence, the intensity distributions normal to boresight are elongated over the rectenna face such that $I/I_o(\Delta\Theta_x, \Delta\Theta_y) = I/I_o(x,y)$, where

$$x, y \approx r\Delta\Theta_x/\cos\Theta_{xo},\ r\Delta\Theta_y/\cos\Theta_{yo}$$

are the coordinates on the horizontal rectenna (see fig 26). The apparent indeterminancy at the boresight can be evaluated by L'Hospital's rule which gives $I_o/I_o = 1$; a local peak, as expected. However, a major constraint on the number of individual radiation sources N^2 is the avoidance of grating lobes -- off boresight peaks which develop when the numerators of the array pattern functions equal zero anywhere in the semi infinite half-space above the transmitter. To avoid them we need $\Psi_x/2, \Psi_y/2 < \pi$. Since $|sin\Theta_x - sin\Theta_{xo}| \lesssim 2$, this condition requires $\ell < \lambda/2$ $(N > 2D_t/\lambda)$. To compute the power incident on the rectenna, we want to recast the idealized intensity pattern with the rectenna coordinates (x,y) as the independent variables. Since $h = r cos\Theta_o$, the angular displacements are expressible in terms of the rectenna coordinates from foregoing relations as:

$$\Delta\Theta_x, \Delta\Theta_y \cong (x/h)\cos\Theta_o\cos\Theta_{xo},\ (y/h)\cos\Theta_o\cos\Theta_{yo}\,.$$

Since, moreover, in the absence of grating lobes the beam is confined to small angular deviations,

$$\Psi_x \cong k\ell\Delta\Theta_x\cos\Theta_{xo} \cong \frac{2\pi x D_t\cos\Theta_o\cos^2\Theta_{xo}}{\lambda h N},$$

$$\Psi_y \cong k\ell\Delta\Theta_y\cos\Theta_{yo} \cong \frac{2\pi y D_t\cos\Theta_o\cos^2\Theta_{yo}}{\lambda h N}.$$

We can therefore write the intensity distribution on the rectenna in the more convenient form:

$$\frac{I(\hat{x},\hat{y})}{I_o} = \left\{\frac{\sin\frac{\pi\hat{x}}{2}}{N\sin\frac{\pi\hat{x}}{2N}}\right\}^2 \times \left\{\frac{\sin\frac{\pi\hat{y}}{2}}{N\sin\frac{\pi\hat{y}}{2N}}\right\}^2,$$

where

$$\hat{x} = \frac{x}{(\lambda h)/(2D_t\cos\Theta_o\cos^2\Theta_{xo})},$$

$$\hat{y} = \frac{y}{(\lambda h)/(2D_t\cos\Theta_o\cos^2\Theta_{yo})}$$

are dimensionless rectenna coordinates containing diffraction and incidence angle effects. The utility of this transformation is that I/I_o distribution is now expressed as a universal function of the dimensionless coordinates $(\hat{x},\hat{y})$. Figure 27, for example, shows this phased array intensity distribution over the rectenna in the $\hat{y} = 0$ plane. (The distribution becomes independent of the number of elements when N is large enough to avoid grating lobes.) The nulls at $\hat{x} = \pm 2, 4,...$ define the boundaries of low-intensity sidelobes produced away from the main lobe. To compute the reception efficiency, we approximate the phased array illumination pattern by the two dimensional Gaussian distribution,

$$\frac{I(\hat{x},\hat{y})}{I_o} \cong exp(-\hat{x}^2) \times exp(-\hat{y}^2),$$

whose spatial integrals can be expressed as error functions. As shown in Fig. 28, this 2D Gaussian is a close approximation to the phased array formula over the central zone where beam power is concentrated.

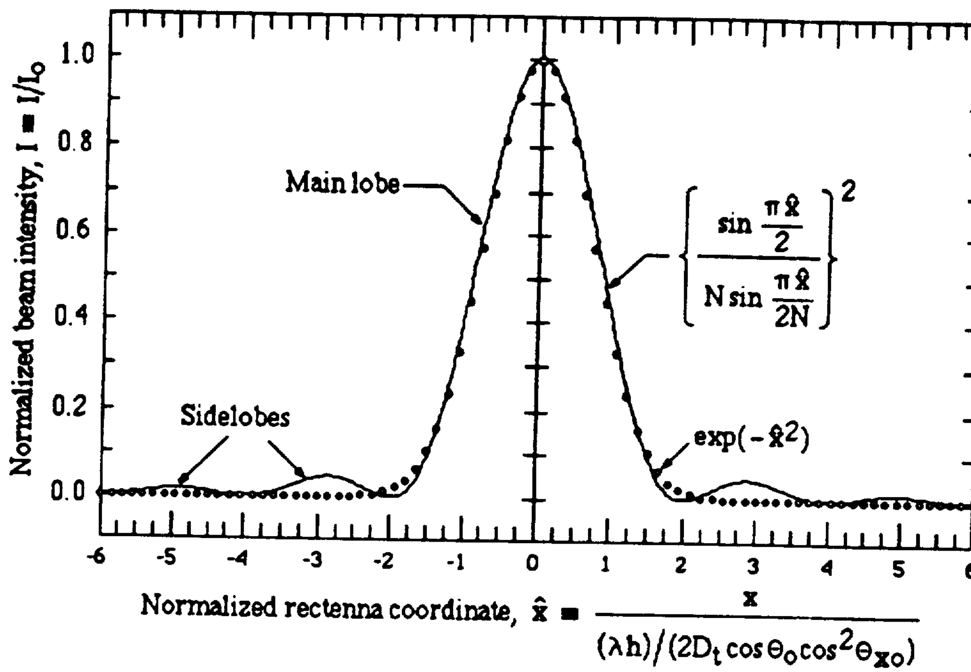


Figure 27. Dimensionless intensity distribution versus dimensionless x-coordinate along the rectenna at y = 0 from the phased array model compared with a Gaussian beam.

We find power incident on the rectenna P_r by integrating the 2D intensity distribution over an area element $dxdy$ between the rectenna edges at $x = \pm D_r/2$ and $y = \pm D_r/2$. The result is expressible in terms of the scan angles and a powerlink parameter, $\chi \equiv \frac{(D_t D_r)}{(\lambda h)}$ as :

$$P_r = \pi I_o \left\{ \frac{D_r}{2\chi \cos\Theta_o \cos\Theta_{xo} \cos\Theta_{yo}} \right\}^2 erf(\chi \cos\Theta_o \cos^2\Theta_{xo}) \times erf(\chi \cos\Theta_o \cos^2\Theta_{yo})$$

where the error function is defined as :

$$erf(z) \equiv \frac{2}{\sqrt{\pi}} \int_0^z exp(-t^2)\, dt \; .$$

Since erf $(\infty) = 1$, the total transmitted power incident on an infinite rectenna is

$$P_t = \pi I_o \left\{ \frac{\lambda h}{2D_t \cos\Theta_o \cos\Theta_{xo} \cos\Theta_{yo}} \right\}^2 ,$$

which defines I_o in terms of the transmitted power, wavelength, altitude, transmitter aperture and the scan angles. A finite rectenna sees the same central intensity only intercepts a fraction of the transmitted power. This fraction is the instantaneous reception efficiency.

$$\eta_r \equiv P_r / P_t = erf(\chi \cos\Theta_o \cos^2\Theta_{xo}) \times erf(\chi \cos\Theta_o \cos^2\Theta_{yo}).$$

An important parameter that permits sizing of the antenna and rectenna system, is the power link parameter χ. Since the scope of the present study is limited to the analysis of surface based point - to - point power beaming, the reception efficiency is evaluated as a function of χ , assuming that, $\Theta_o = 0$ and $\phi_o = 0$. Figure shows a plot of χ versus η_r . The power link parameter was assumed to be $\chi \approx$ 1.4, consequently permitting the sizing of the antenna and rectenna sizes which yields a reception efficiency of 90 %.

Several beam power models have been formulated in connection with the study of either the Solar Power Satellite by Gobau [30] Suddath [31] Arndt and Kerwin [32] or in connection with the recent resurgence of interest in beam power as an effective means of supplying space power (see Kai Chang et al [27]). However these models have not been intercompared and we have undertaken to do so in a limited manner in this study. The models which can be used for the analysis of point - to - point beaming are that of Arndt and Kerwin, the work of Kai Chang et al (which is based on the optimization of the gain taper imposed on the antenna by Suddath [31]) and the model of Hoffert et al [7] and [8] (which has been extended in this study). Since the analysis in this study does not impose a taper on the antenna, the only comparison possible at this time is between the "uniform taper" case studied by Arndt and Kerwin and the model in the present study.

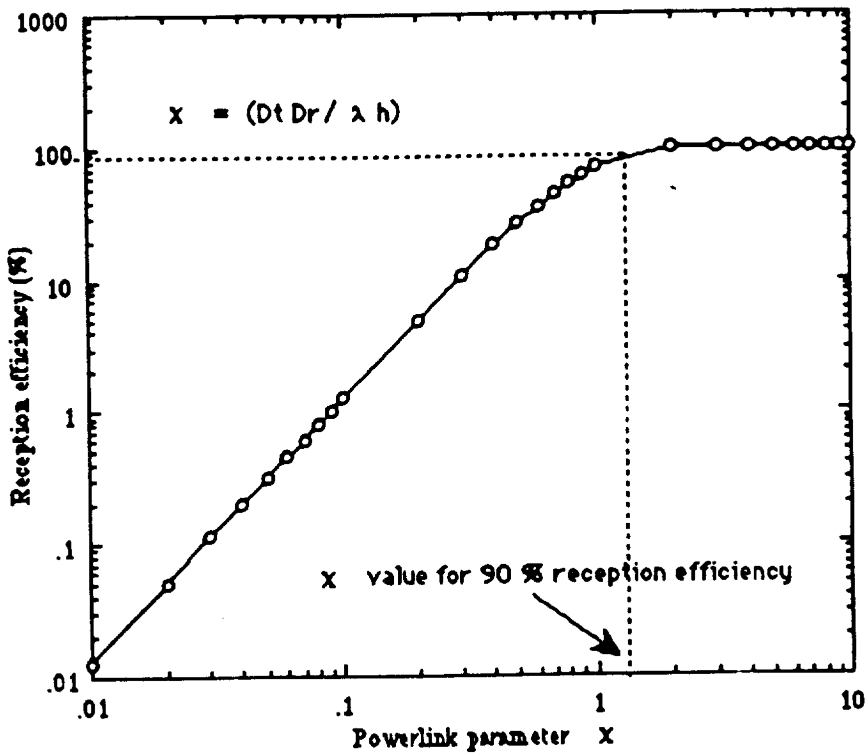


Figure 28. Reception efficiency versus powerlink parameter. Powerlink parameter of 1.4 yields an efficiency of 90%.

The power reception efficiency in Arndt and Kerwin's model is given by :

$$\eta_r \equiv P_r / P_t = 1 - J^2{}_0 (u) - J^2{}_1 (u)$$

where,

$$u = \frac{2 \pi R_r R_t}{\lambda h}$$

and the expression for efficiency from the model in the present study is :

$$\eta_r \equiv P_r / P_t = (erf(\chi))^2$$

where,

$$\chi = \frac{D_t D_r}{\lambda h}$$

Figure 29 compares the model in the present study with that of Arndt and Kerwin in the far field. This is because the Arndt and Kerwins model shows a degradation in the near field. The antenna and rectenna sizes have been fixed at five and ten metres respectively in this intercomparison study.

On the left hand figure efficiency versus range is depicted at a frequency of 35 GHz. On the right hand figure efficiency versus frequency is compared. There seems to be good agreement of the two models for low values of the powerlink parameter.

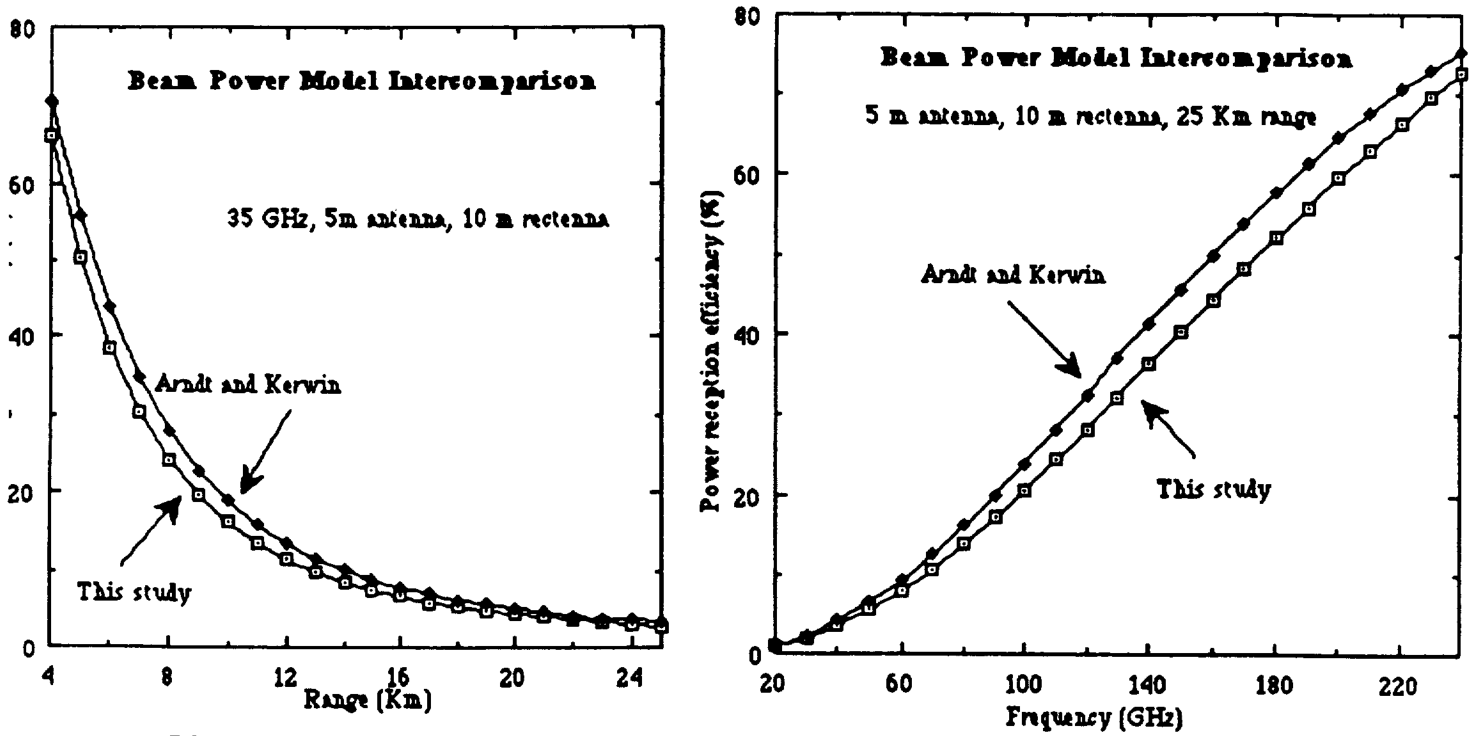


Figure 29. Beam power models developed by Arndt and Kerwin is compared to the model developed by Hoffert et al (and extended in the present study).

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